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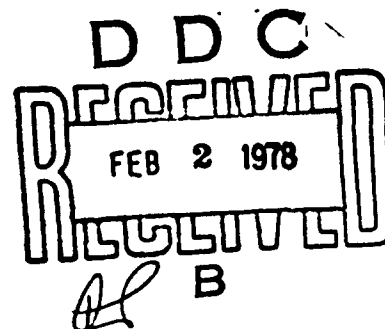
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TO: AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
   Building 410
   Bolling Air Force Base
   Washington, D.C. 20332

ON: THE VAPORIZATION BEHAVIOR OF A FUEL DROP
   ON A HOT SURFACE

   AFOSR 76-2876

Submitted by

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# TABLE OF CONTENTS

Page

i

# LIST OF FIGURES

## LIST OF TABLES

INTRODUCTION

In atomizing liquid fuel for combustion, very often
a portion of the fuel impinges on the wall of the
combustion apparatus. The evaporation of the deposited
fuel influences the air/fuel mixture formation in the
apparatus and, therefore, the combustion rate and
efficiency.

Fuel droplets are known to impinge on the wall
of the gas turbine engine. Maybach (1955) reported that
the deposition of fuel on the combustor wall is encouraged
in specific gas turbine applications to enhance fuel
vaporization and improve the combustion characteristics.

The importance of the formation of air/fuel mixtures
in a combustion apparatus by depositing the fuel intention-
ally or accidentally on hot surfaces makes the topic of
this research study of interest in the field of combustion.
Several workers have investigated drop evaporation on a
hot surface in an effort to identify parameters that may
influence or control the vaporization of the deposited
fuel. The experimental investigations of the drop evaporation
were conducted at subcritical and supercritical conditions
of pressure and temperature. A survey of this research
was made and important findings reported by the various
investigators are summarized below.

Tamura and Tanasawa (1959) were among the first to
investigate the evaporation and combustion of fuel drops in
contact with a hot surface. Their experiments were
conducted under atmospheric pressure, where a fused quartz
plate, heated by hot air was used for the evaporation of the drops.

Adadevoh et al. (1963) investigated fuel drop evaporation under ambient pressure of up to 7 atmospheres. Their research objective was to determine the effect of pressure on the surface temperature at which drop maximum rate of evaporation occurred.

Temple-Pediani (1969-1970) also investigated fuel drop evaporation under high ambient pressures (up to 69 atmospheres). The objective of the study was to identify the evaporation behavior of fuel drops deposited on a hot surface under subcritical and supercritical conditions of pressure and temperature.

Satcunanathan et al. (1968) were among the first to investigate the ignition of fuel drops deposited on a hot surface. The apparatus used consisted of a small electric furnace used to heat a quartz disc upon which fuel drops were deposited for combustion. The ignition space consisted of the furnace cover, which was machined from refractory clay and fitted tightly over the disc. The furnace electrical heating element was supplied from the mains through a variable transformer to allow modulation of furnace temperature.

## Evaluation of Reviewed Investigations

In reviewing the previous investigations, significant differences were noted in the evaporation lifetime reported by the various workers for fuel drops of the same type and comparable size. The disagreement between the investigators was also evident in reporting the temperature range within which the various modes of drop evaporation occurred.

To examine the differences in the reported test results, the evaporation curves developed by Tamura et al.; Adadevoh and Temple-Pediani for n-Hexadecane under atmospheric pressure are compared in Figure 1. The figure showed that the evaporation lifetimes reported by Temple-Pediani were generally shorter than those reported by Tamura et al. for all modes of drop evaporation in spite of the fact that Temple-Pediani used a substantially larger fuel drop in conducting his investigation. The evaporation lifetimes for the contact mode in Temple-Pediani's study were also far less sensitive to changes in surface temperature, when compared with the results of Tamura et al. and Adadevoh. The evaporation curve developed by Adadevoh on the other hand showed no indication whatsoever for the maximum boiling point or the Leidenfrost point (spheroidal lifting). The evaporation lifetimes for the spheroidal mode in Adadevoh's results were substantially shorter than that reported by other workers and
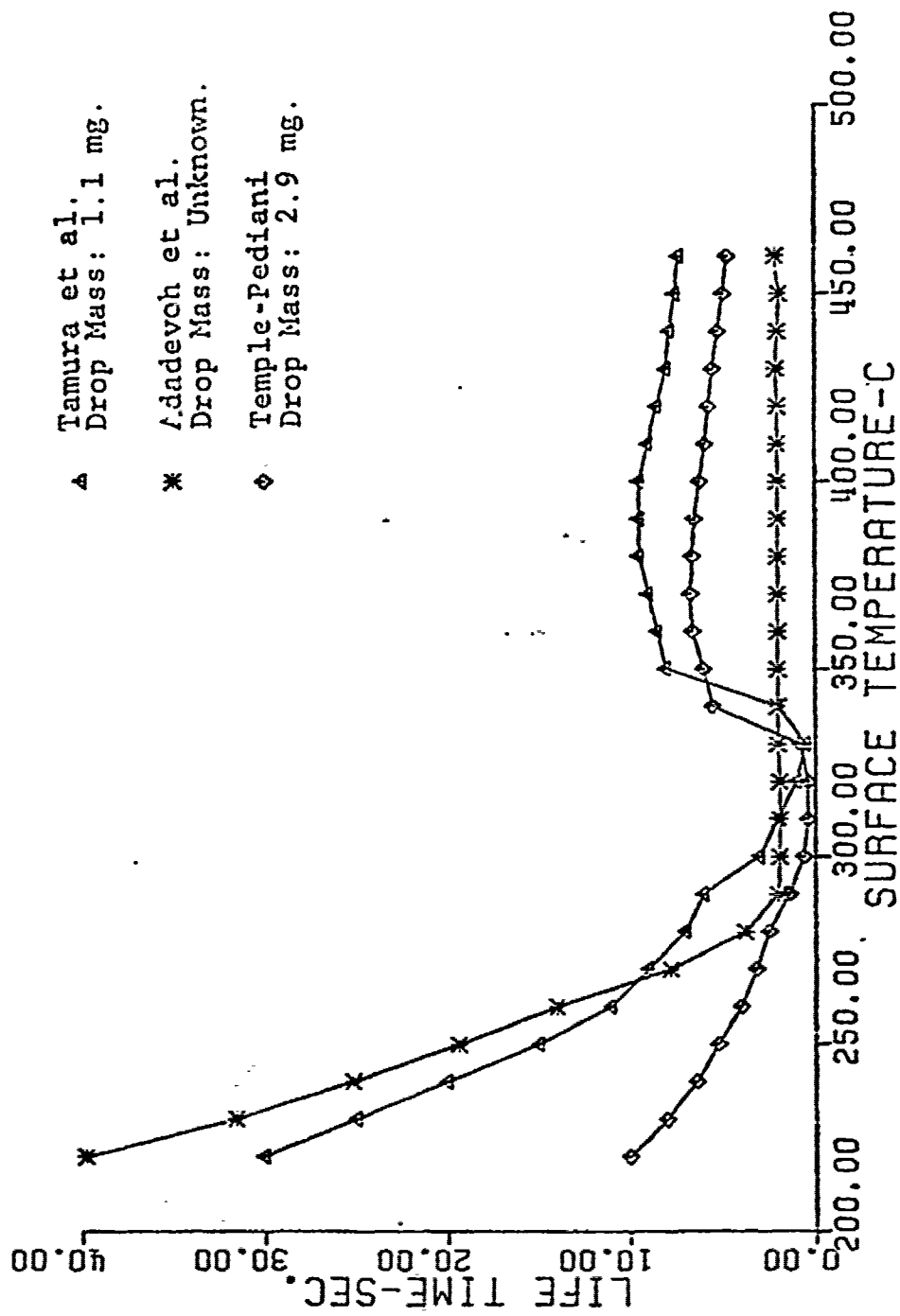
Figure 1.  Comparison between the evaporation curves
reported by previous investigators.

appeared to be independent of the surface temperature.
The temperature ranges within which the various modes of
evaporation occurred were also different in the various
investigations.

In view of the fact that the same pure fuel was
used in conducting these investigations, it was reasonable
to assume that apparatus variables and/or experimental
procedures influenced the discrepancies noted in the
results. The degree by which the experimental variables
affected the results in each investigation was not known.
Unfortunately, no attempt was made by previous workers
to identify the effect of experimental variables on the
result of their respective investigation.

## Scope of Present Study

This research was carried out in order to obtain
better understanding of the mechanism controlling drop
evaporation on a hot surface. In conducting the investiga-
tion, an extensive effort was initially devoted to achieve
reliable data reproduction and to identify the effect of
experimental variables on the test results. Experimental
techniques such as the capability to reproduce fuel drop
size, plate heating rate, and surface characteristics were
all optimized to achieve satisfactory reproduction of the
data. The experimental apparatus was designed and built
to minimize the dependence of the results on apparatus
variables.

In this investigation, the effect of fuel properties on evaporation lifetime in the various modes of evaporation was closely examined. Fuel properties that influenced or controlled the temperature range over which the various modes of evaporation prevailed were successfully identified. The effect of the evaporating surface characteristics on evaporation lifetime and the reproducibility of the results was also determined. Evaporation curves were developed using a wide selection of surface conditions, some of which resembled surfaces encoun.ered in actual combustion applications.

Evaporation curves for a variety of pure and commercial fuels were developed and the evaporation behavior of these fuels was discussed and compared. The effect of fuel additives on the evaporation of the investigated fuels in various modes of evaporation was discussed. Techniques to broaden the temperature range over which the maximum rate of evaporation is obtained were recommended. The mechanisms by which a variety of commercial fuel additives brought about an improvement in the combustion quality of the fuel in the various combustion applications were also qualitatively evaluated.

## Description of Experimental Apparatus

A diagrammatic view of the experimental apparatus
used in this investigation is shown in Figure 2.  The
apparatus consisted of an evaporating surface (1), 4½" W. x
4½" L. x ¼" H. manufactured of stainless steel 403. Eighty
one evaporating dishes (spherical depression) ½ DIAX 0.15"D
were machined on the evaporating surface for the evapo-
ration of the various fuel drops.  The evaporating dishes
after machining were polished to a mirror-like surface
finish using special abrasive rubber polishing wheel.  Two
additional evaporating surfaces were made with a large flat
recess machined on its center one from stainless steel 403
and the other from aluminum.  Results obtained using the
stainless steel and aluminum surfaces were compared to
identify the effect of surface material on evaporation
lifetime.  The effect of evaporating surface geometry on
drop evaporation was also determined by comparing the
results obtained using the stainless steel surfaces with
evaporating dishes and with a flat recess.

To heat the evaporating surface, the surface was
tightly clamped by four 3/16" DIA. studs to a Watlow
Ferroide flat electric heater (2) 5" W. x 5" L.  The
electrical heater had a uniform heating density of 35 watts
per square inch and a total heating capacity of 875 watts.
The dimension  of the heater was selected slightly larger
than the evaporating surface to insure firm contact
between the heater and the surface especially around the

(1) Evaporating surface
(2) Electric heater
(3) Copper plate
(4) Fuel container
(5) Injector tip
(6) Metering valve
(7) Selenoid valve
(8) Injector braket

Figure 2.     Diagramatic view of the
              experimental apparatus.

perimeter. In spite of the fact that the heating elements were evenly distributed within the heater spot over-heating was experienced in the evaporating surface at the location of these elements. To avoid the formation of local hot spots, a copper plate (3) 5" W. x 5" L. x 1/8" H. was inserted in between the evaporating surface and the electrical heater. The high thermal conductivity of the copper plate in comparison to the interfacing thermal conductivity between the copper plate and the evaporating surface enhanced heat conduction within the copper plate which resulted in a fairly uniform temperature distribution within the plate. Exposing the evaporating surface to a heating source (copper plate) that is maintained at a uniform temperature minimized to a great extent the tempe-rature gradients within the surface and virtually eliminated spot overheating. To regulate the evaporating surface temperature, the electric heater was connected to the main outlet through a variable transformer. Modulating the transformer setting varied the voltage input to the heater which in turn regulated the heating rate and the temperature of the surface.

The fuel drops were formed by allowing the fuel to flow under its own static head from the fuel container (4) to the injector tip (5). The rate of fuel flow through the injector was regulated to the desired level by a Nupro fine

metering valve (6). The metering valve was equipped with vernier handle, so that, it is possible to reset the valve to exactly the same setting during the various experimental runs. The fuel container was sized sufficiently large so that the fuel feeding static head was maintained relatively constant during the entire experimental run. Maintaining the fuel feeding head constant insured uniform fuel feeding rate during the injection of the various fuel drops which in turn insured uniform drop size.

The size of fuel drop formed was only dependant upon the geometrical configuration of the injector tip (5) and the surface tension and specific gravity of the fuel used. To change the size of the fuel drop formed, injector tips of different geometrical configurations were used. Maintaining variable influencing the drop size unchanged, readily insured the desired reproducibility in drop size.

The injection of fuel drops was controlled by a Skinner Sub-Minature selenoid valve (7) which is normally closed. The valve was energized opened by a 3-way momentary switch. Positioning the momentary switch to position A energized the selenoid valve open and allowed a fuel drop to slowly grow on the injector tip. When the drop reached a certain maximum size it separated off the injector and started to fall onto the evaporating surface. Releasing the momentary switch to the neutral position

de-energized the selenoid valve and instantly stopped fuel
feeding through the injector.

To minimize the effect of radiant heat from the
evaporating surface on the fuel temperature within the
injector, the injector was water jacketed. The flow rate
of cooling water around the injector was regulated by the
laboratory faucet to insure a uniform fuel temperature
during the entire experimental run. Maintaining the
initial temperature of the fuel drops constant enhanced the
accuracy of the test results and improved data reproduction

The fuel injector assembly was installed on a bracket
(8) which allowed the adjustment of the injector position
in both the vertical and horizontal plans. The injector
itself was installed on a rotating arm of a variable length
radius so that it could be positioned above the various
dishes machined on the evaporating surface. The injector
was adjustable in the vertical plane by a sliding assembly
provided in the supporting column for the injector bracket.

An electronic digital stopwatch was specially built
for the measurement of the drop evaporation lifetime. The
watch was electrically activated by the same momentary
switch that is used to energize the selenoid valve for the
injection of fuel drops. The electrical circuit of the
stopwatch was designed such that by positioning the
momentary switch to position A to energize the selenoid

valve, the watch was automatically reset to zero setting.
The watch was activated by positioning the momentary
switch in the opposite position B and was stopped by
releasing the momentary switch to the neutral position.
Resetting the watch automatically to zero setting prior to
the injection of a fuel drop minimized the potential of
making an error in determining the drop evaporation
lifetime.

The temperature of the evaporating surface was
determined by a grounded Chrom-Alumel thermocouple. The
thermocouple was shielded in an 1/8" DIA. stainless probe
and the probe was inserted within the evaporating surface.
The thermocouple output was displayed by a Doric, series
400, temperature trendicator. The Doric instrument was a
solid-state, analog to digital, temperature measuring
indicator which digitally displayed the thermocouple
inputs in degrees Centigrade. The instrument had a
measuring speed of 3 readings per second and provided a
resolution of 1 Deg. C using a standard thermocouple.

### Description of the Experimental Procedure

The experimental procedures were optimized to improve
the accuracy of the test results and achieve satisfactory
reproduction of the data. Special effort was made in
developing the procedure to insure the reproducibility ·

of the evaporating surface heating rate and surface con-
dition, and to maintain the size consistency of the fuel
drops. The optimum test procedures were identified by
trial and error during the refinement effort of the
experimental apparatus. The procedures adopted were
broken down to three major steps:

(1) Preparation of Fuel Injection System. Prior to
each test run, the fuel injection system was
cleaned by a hydrocarbon solvent
(Trichloroethylene $C_2H Cl_3$) to remove fuel
residue that may have remained in the system
from previous testing. The used solvent, due to
its high volatility, dried from the injection
system at room temperature in a relatively short
period of time. After the solvent was dried, a
disc of Whatman filter was placed inside the
fuel container to prevent solid particles from
being entrained with the fuel. The tested fuel
was then poured into the fuel container and the
fuel metering valve was placed in the wide open
position. The momentary switch was then posi-
tioned to position A to energize the selenoid
valve open and allow fuel to flow through the
injector. Sufficient amount of fuel was drained
through the injector to flush the residue of

other fuels and to bleed out the air entrapped
in the injection system.

To achieve optimum reproducibility of fuel
drop size, the fuel metering valve was then
reset to a specific setting using its vernire
handle. The optimum setting of the valve
varied somewhat with the type of fuel used. In
general, the valve setting was such that, fuel
feeding rate to the injector tip is relatively
slow to insure stable growth of the drop and
eliminate the effect of liquid swirling within
the drop on drop size reproducibility.

The formed fuel drops were weighted by
depositing ten drops onto the pan of a torsion
balance. The balance is equipped with a
graduated dial so that the weight of the drops
could be dialed without the use of external
weights. The weighing of the drops was repeated
three times to insure reproducibility and the
average drop weight was recorded. In general,
the drop weight was reproducible within the
accuracy limits of the torsion balance ($\pm$ 2mg).

(2) Preparation of Evaporating Surface. To insure
that the fuel drops are exposed to a surface
finish of uniform quality the evaporating dishes

were cleaned and polished to a mirror-like
surface finish before each test run. The dishes
were polished by felted polishing wheel and a
special buffing compound to remove fuel residue
left on the surface from previous testing. The
waxy buffing compound remained on the surface
after the cleaning process was removed by a
paper tissue dipped in an organic solvent
(trichloroethylene $C_2H\ Cl_3$).

The copper plate, inserted between the
evaporating surface and the electrical heater,
was also removed to be cleaned before each test
run. The plate was scrubbed with steel wool,
soap and water to remove copper oxides that may
have formed on its surface due to exposure to
high temperatures. The evaporating surface and
the copper plate were then tightly clamped to
the electrical heater by four 3/16" DIA. studs
to insure positive contact between the various
surfaces.

(3) Construction of Drop Evaporation Curves. The
evaporation curves were developed by plotting
the drop evaporation lifetime against the
surface temperature. The temperature range over
which the fuel evaporative behavior was.

investigated varied for the various fuels.
The investigated temperature range was selected
sufficiently large to cover all modes of drop
evaporation.

In developing the evaporation curve for a
specific fuel, the evaporating surface was very
slowly heated to the temperature range to be
investigated. The heating rate of the surface
was closely controlled by modulating the
voltage input to the electrical heater using a
variable transformer. The heating time of the
surface took on the average 15-30 minutes to
insure uniform temperature distribution within
the evaporating surface.

When the evaporating surface reached the
desired temperature level, the injector was
positioned by hand above one of the evaporating
dishes. The momentary switch was then turned
to position A to energize the selenoid valve
open and allow a fuel drop to slowly grow on
the injector tip. When the drop reached a
certain maximum size it separated from the
injector tip and started to fall onto the
evaporating surface. The momentary switch was
then released to the neutral position to.

de-energize the selenoid val    .nd stop fuel
feeding through the injecto . As so.n as the
drop contacted the evaporating ".. .ace, the
momentary switch was turned to position B to
start the digital watch. The switch was held
in this position until the drop completely
evaporated. Releasing the switch to the
neutral position upon the complete evaporation
of the drop stopped the watch and allowed the
determination of drop evaporation lifetime. The
same procedure was identically repeated to
determine drop evaporation lifetime at a
different surface temperature.

The drop evaporation lifetime was deter-
mined in the investigated temperature range
every 10 Deg. C. The surface temperature was
slowly increased by increasing the variable
transformer setting in small increments. The
transformer setting at the different surface
temperatures was recorded so that it is
possible to reproduce the surface heating rate
during other test runs. The surface heating
rate was regulated such that the change in the
surface temperature during the evaporation
lifetime of a drop was not more than 2 Deg. C.

The evaporating dish was used only once
during an experimental run for the evaporation
of a single drop. The dishes were used in both
random and sequential manner and the obtained
results were compared to show that the repro-
ducibility of the results is not dependent upon
any sequential use of the evaporating dishes.
The evaporation curves for each fuel and for
each drop size were repeated at least two times
to insure that satisfactory reproduction of the
data is obtained.

# EXPERIMENTAL RESULTS AND DISCUSSION

## Evaporation Behavior of Fuel Drops on a Polished Metal Surface

Evaporation curves were developed for a variety of
pure and commerical fuels to identify the modes of drop
evaporation for different types of fuels. Four pure fuels
were selectively tested during the investigations to cover a
wide range for the various fuel properties. The tested
fuels were n-Heptane; 1-Octene; 1,2,3,4-Tetrahydronaph-
thalene; and n-Hexadecane. The evaporation behavior of
other fluids such as no. 2 commercial diesel fuel and pure
distillate water were also examined. The experimental
investigation was conducted using the optimized experi-
mental apparatus equipped with the stainless steel
evaporating surface that had polished evaporating dishes
machined on its surface to achieve the optimum level of
experimental accuracy and reproducibility.

## The Evaporation Behavior of Pure Fuels

Evaporation curves for n-Heptane; 1-Octene, 1,2,3,4-
Tetrahydronaphthalene; and n-Hexadecane are presented in
Figures 3 through 6 respectively. Each evaporation
curve presented in these figures represents the arithmetic
average of two experimental runs. As discussed earlier, a
high degree of experimental reproducibility was generally
obtained with pure fuels due to the uniformity in the fuel
properties. The evaporation curves for n-Heptane and for
n-Hexadecane were developed, as shown in Figures 3 and 6
for several drop sizes in order to determine the effect of
the drop size on its evaporation behavior.

Four basic modes of drop evaporation were identified
for the tested fuels; the contact mode, the vaporization
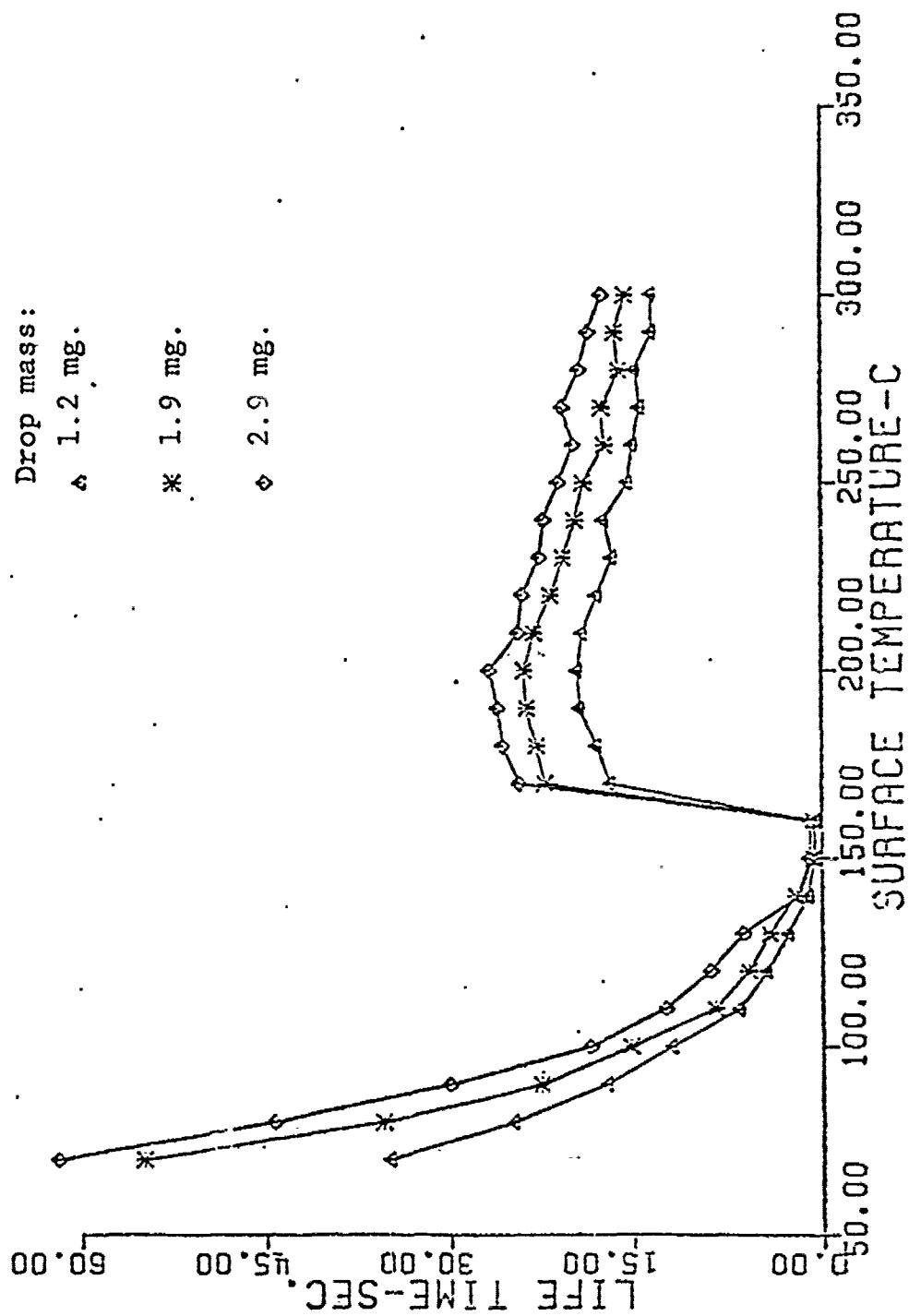
Figure 3 .   Evaporation lifetime for n-Heptane.
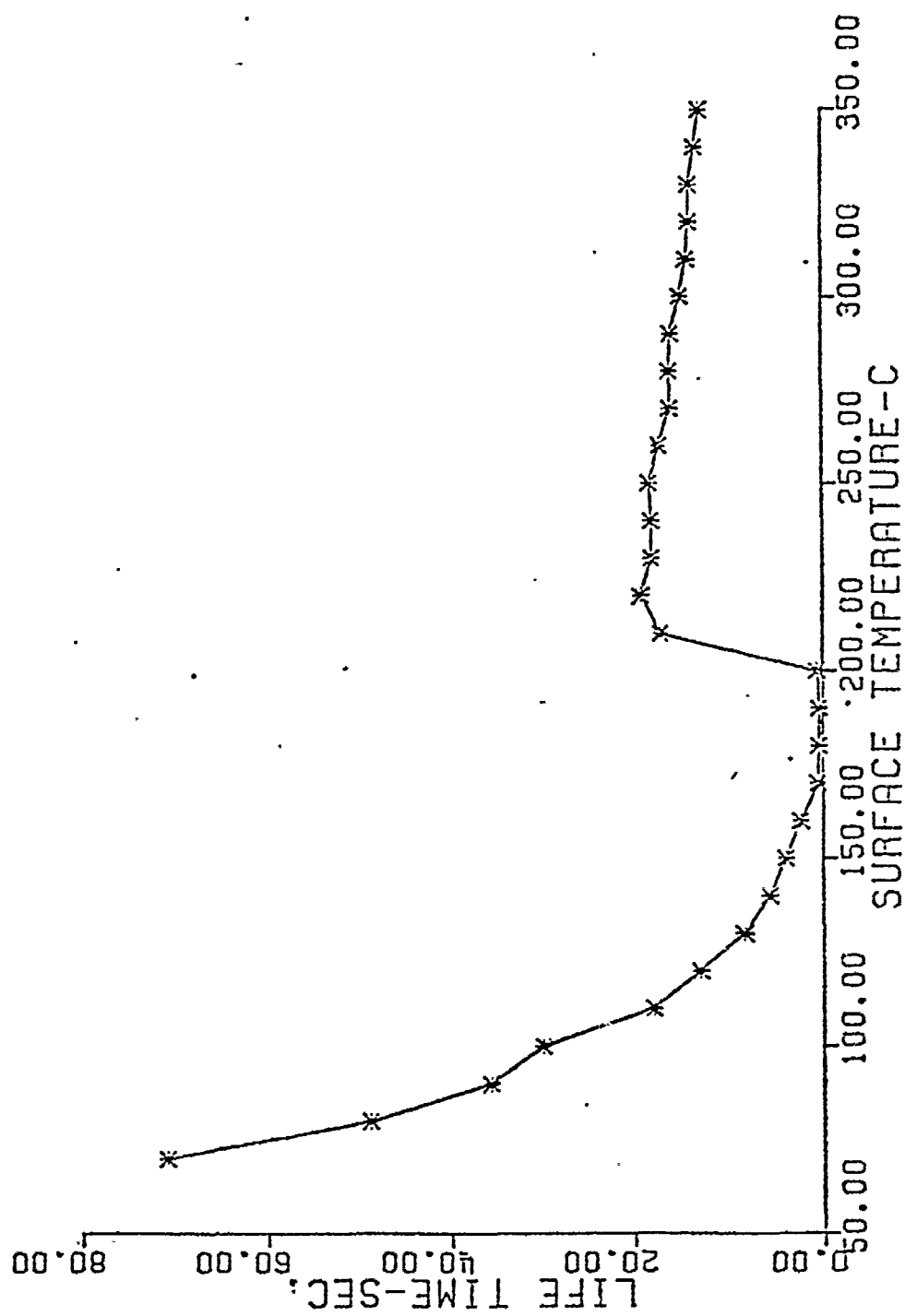
Figure 4. Evaporation lifetime for 1-Octene.
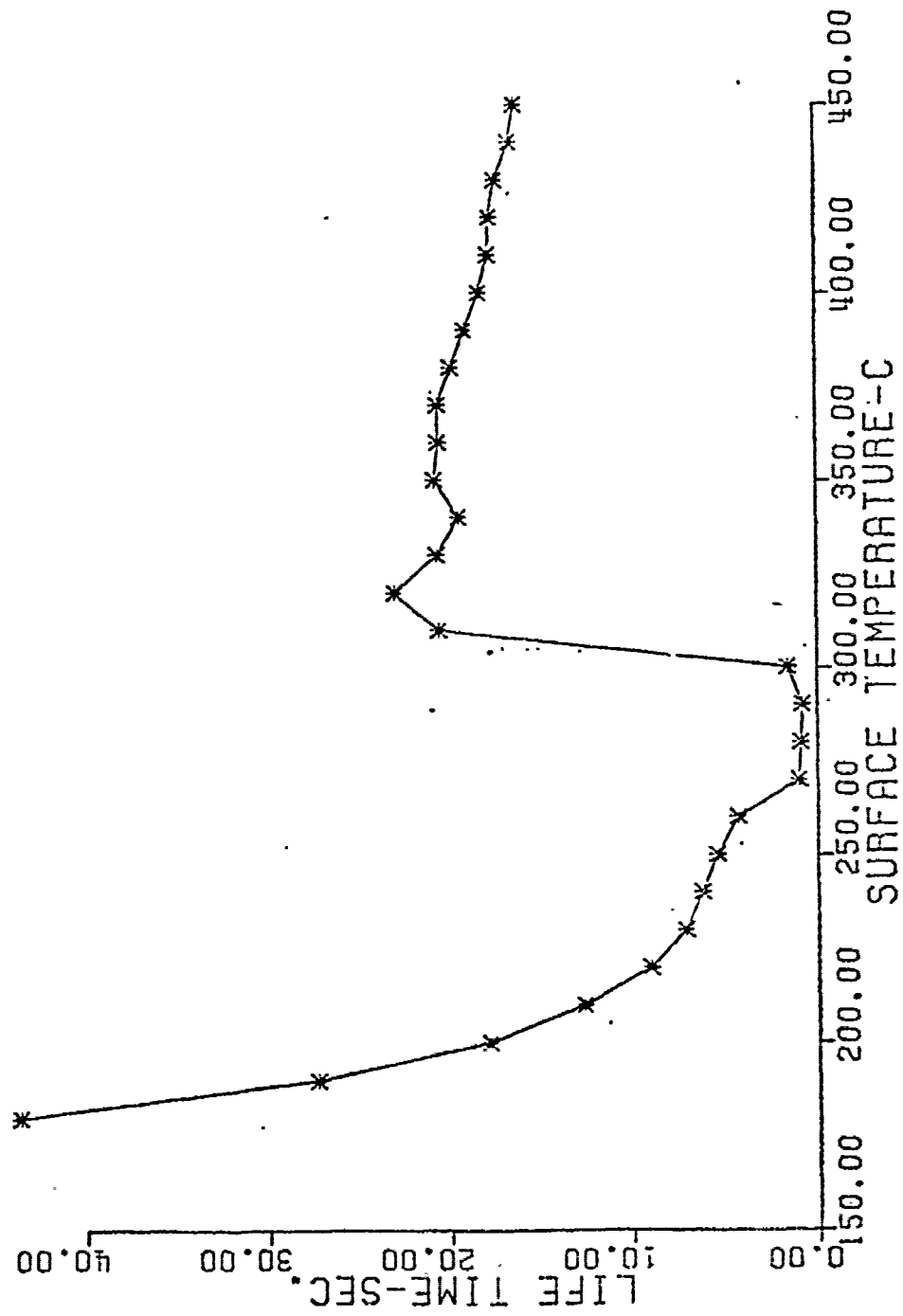
Figure 5 .    Evaporation lifetime of 1,2,3,4-Tetrahydronaphthalene.
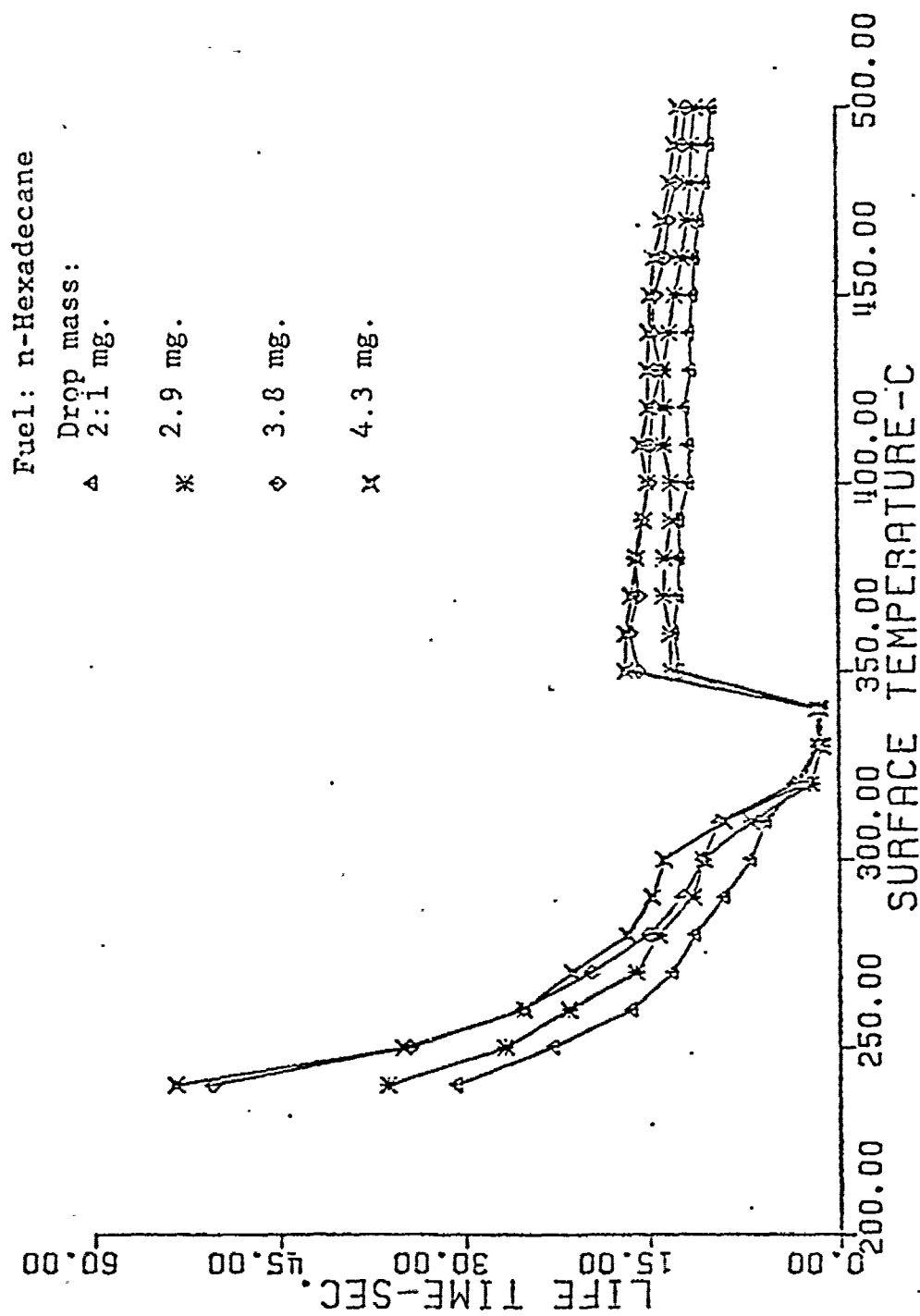
Figure 6.  Evaporation.lifetime for n-Hexadecane.

mode, the maximum evaporation mode, and the spheroidal mode
of evaporation. The identified modes of evaporation were
generally in agreement with the modes described by previous
workers. For the n-Heptane and 1-Octene only a faint
indication was displayed by the evaporation curves for the
surface temperature at which transition occurred from the
contact mode to the vaporization mode of evaporation. The
surface temperature for the transition from the maximum
evaporation rate mode to the spheroidal mode was clearly
indicated, however, for all fuels by an abrupt vertical
discontinuity in the evaporation curves. To describe the
identified modes of evaporation a typical evaporation curve
was re-drawn in Figure 7 with the temperature range for
the various modes denoted on it in letters. The drop eva-
poration behavior during the various modes was observed
to be as follows:

(1) Contact Mode (a-b)

In the contact mode the drop fell onto the
surface and very rapidly spread to partially
fill the evaporating dish. Fuel evaporation
commenced upon drop contact with the surface
and evaporation of the fuel progressing at a
steady rate caused a continuous reduction in
the liquid volume. The fuel contact with the
surface was permanently maintained during this
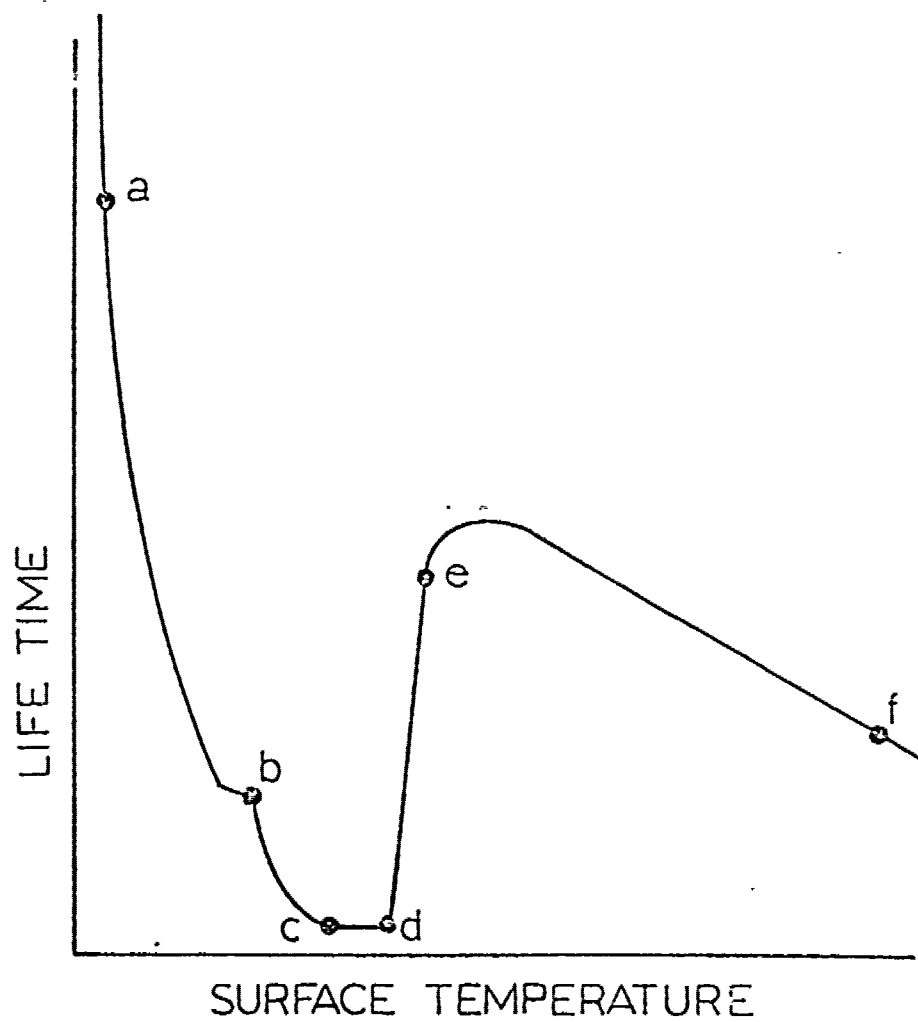
Figure 7. The modes of drop evaporation.

mode and mass transfer took place only from the
phase boundary exposed to the atmosphere. The
drop evaporation lifetime in this mode was
proportional to the latent heat of vaporization
of the fuel. For a specific fuel, the incre-
mental reduction in drop evaporation lifetime
due to an increase in the surface temperature
appeared to be proportional to the increase in
fuel vapor pressure with temperature. This
strongly indicated that the controlling mecha-
nism for drop evaporation in this mode is the
rate of vapor diffusion at the drop phase boun-
dary that is exposed to the atmosphere. The
drop lifetime in the contact mode was also found
to be very dependent upon the contact area
between the drop and the evaporating surface.

(2) Vaporization Mode (b-c)

In this mode, when the drop first contacted
the surface, several nucleation sites started
to develop at the interface between the drop
and the surface. Increasing the surface tempe-
rature increased the number of nucleation sites
formed and progressively reduced the drop evapo-
ration lifetime. As the maximum evaporation rate
mode was approached the drop evaporation became

very noisy and liquid lifting off the drop by
the expanding vapor occasionally took place.
The drop evaporation lifetime in this mode was
critically dependent upon contact area, between
the drop and the surface, and therefore, its
evaporati n lifetime was sensitive to surface
tension of the fuel. The mode was regarded as a
transition mode between the contact mode of eva-
poration and the maximum evaporation rate mode.

(3) Maximum Evaporation Rate Mode (c-d)·

During this mode a transition took place
from the evaporation with the shape of a flat
film to evaporation with the shape of an ill-
defined part sphere. The drop evaporation was
very violent and noisy and commenced as soon as
the drop contacted the surface. The evaporation
of the drop was again very sensitive to the area
of contact between the drop and the evaporating
surface. The drop evaporation lifetime appeared
to be influenced by the dynamics of heat transfer
to the drop, more so than by properties of the
fuel itself. Due to the high intensity of the
heat flux that is transferred to the drop in
this mode, severe localized surface cooling
occurred, especially with surfaces of a poor

thermal conductivity, The drop evaporation in this mode was within experimental limits a constant minimum.

(4) Spheroidal Mode of Evaporation (e-f)

During this mode, the drop, following contact with the surface was lifted and permanently supported on a vapor cushion until almost all the liquid evaporated. Early in the lifetime of the spheroidal evaporation, the drop shape was nearly a perfect truncated sphere. As evaporation continued, the shape of the drop gradually changed, to nearly a perfect sphere. The lifting of the fuel drops into the spheroidal mode occurred for the various fuels at a specific surface temperature which was found to be strongly dependent upon the fuel properties and the evaporating surface characteristics. The mechanism of spheroidal lifting was postulated to be as follows.

When a fuel drop is deposited on a hot surface, it spreads over the surface as shown in Figure 8 , in a finite time that is mainly dependent upon the fuel surface tension. As the drop spreads over the surface nucleation sites of vapor pockets develop at the interface
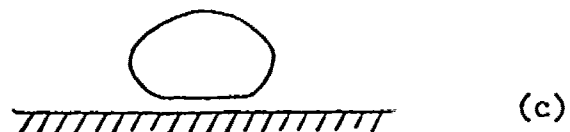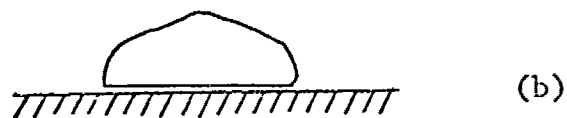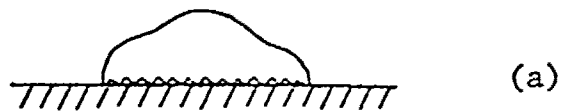
Figure 8 .    Stages for fuel drop
              lifting into the sphe-
              roidal mode.

between the drop and the surface  (Figure 8a ).
If the number of nucleation sites formed was
sufficiently l rge, and if the nucleations were
developed sufficiently fast before the drop
flattened away from the spheroidal shape, a vapor
cushion would form underneath the drop
(Figure   8b) and the spheroidal lifting would
occur (Figure 8c ).  The rate of nucleation sites
formation is obviously dependent upon the
intensity of the heat flux supplied to the drop,
which in turn is a function of the surface
temperature and the thermal conductivity of the
surface.  For a specific evaporating surface,
the surface temperature at which spheroidal
lifting occurs is dependent, based on this
postulate, upon fuel boiling temperature, sur-
face tension, latent heat of evaporation, and
to a lesser degree upon the specific heat of
the fuel.

The drop evaporation lifetime in the
spheroidal mode was very much affected by the
mechanism of spheroidal lifting and the
dynamics of supporting the drop on its own vapor
cushion.  For example, during the initial contact
of the drop with the surface, a delay in drop

lifting off the evaporating surface occurred causing a fraction of the drop mass to evaporate at a very intense rate. The longer the delay period, the larger was the fuel mass fraction that evaporates prior to drop lifting into the spheroidal mode. The evaporation lifetime in the spheroidal mode was as a result somewhat affected by this delay in drop lifting. At a specific surface temperature the delay in lifting was mainly dependent upon the fuel boiling temperature, surface tension, latent heat of vaporization and the specific heat of the fuel. The delay period progressively decreased as the evaporating surface temperature was increased.

The hydrodynamics of supporting the fuel drops on its own vapor cushion in the spheroidal mode of evaporation, on the other hand, affected the termination of drop evaporation lifetime. It was noted that as the drop evaporated in this mode, chemical cracking of the fuel occurred within the drop causing the formation of heavy fuel residue. The occurrence of the fuel cracking was quite evident by the change in the drop color from clear white to dark brown. The

cracking of the fuel was especially noticeable
during the evaporation of fuels of high boiling
temperature, due to the increase in the
cracking process with fuel temperature. The
formation of the heavy fuel residue progressi-
vely reduced the rate of fuel evaporation, which
resulted in the destruction of the vapor cushion
underneath the drop, and the subsequent spla-
shing of the drop onto the surface. The drop
evaporation lifetime in this mode was therefore
affected by the size of the fuel drop when
splashing onto the surface occurred. Fluctua-
tions noted in the drop evaporation lifetime
in the spheroidal mode was generally attributed
to the random variation in the delay of drop
lifting and also to the variation in drop size
when splashing occurred onto the evaporation
surface.

The drop evaporation lifetime in the
spheroidal mode was found to be directly propor-
tional to the drop mass and inversely
proportional to the surface temperature. The
rate of reduction in evaporation lifetime, as a
result of the increasing surface temperature,
was somewhat influenced by the boiling tempera-

ture of the fuel. The drop lifetime in this
mode was generally long due to the insulation
effect of the vapor cushion and appeared to be
predominantly controlled by the dynamics of
heat transfer to the drop.

Previous investigators have reported two additional
modes of drop evaporation which were not described above;
the transition mode and the spheroidal mode of combustion.
The transition mode, according to previous workers, is a
mode of evaporation that occurred between the maximum
evaporation rate mode and the spheroidal mode of evapora-
tion. In this mode, previous investigators described that
the drop upon contact with the surface shattered into
several satellite drops, and the smaller drops started to
dance up and down the surface lengthening the drop
evaporation lifetime. The drop lifetime progressively
increased with the increase in the surface temperature,
until the beginning of the spheroidal mode of evaporation
was reached. The authors indicated that the drop
evaporation in this mode was very unstable and much
scattering of the experimental data was experienced. The
surface temperature range within which the mode of
evaporation occurred was reported by various investigators
to be as much as 60-70 degrees C.

By examining the cause of drop shattering into

smaller drops, it was evident that the occurrence of such incident is directly dependent upon the height of the fuel injector, above the surface and upon the mass of fuel drops used in conducting the experiment. In view of this finding, it appeared that the "transition mode" that was categorized by previous workers as a "mode" of drop evaporation, is merely caused by an apparatus variable rather than by being influenced by the fuel properties. Using the optimized experimental apparatus, it was experimentally demonstrated in the present investigation that the transition mode of evaporation does not exist. As can be seen from the presented evaporation curves, Figures 3 through 6 , the lifting into the spheroidal mode took place at a surface temperature that is only 10 degrees C above the maximum evaporation rate temperature. The surface temperature at which transition to the spheroidal evaporation occurred was, as discussed earlier, dependent upon the fuel properties and the characteristics of the evaporating surface.

The spheroidal combustion was first reported by Tamura and Tanasawa in 1959. Subsequent investigations, conducted by Satcunanathan et al. (1968) and Temple-Pediani (1970), on the spontaneous ignition and ignition delay of fuel drops deposited on a hot surface further explained the mechanism of spheroidal combustion. It was described by

the authors that during the drop evaporation in any mode, vapor diffuses progressively from the drop to the surrounding oxidant. This vapor forms a reacting mixture with the oxidant and starts to burn at a moderate rate. They indicated that the reaction will be accelerated to ignition when and where the following conditions are simultaneously satisfied:

(1) A vapor concentration gradient exists between the boundaries of the Lean Limit of flammability and a rich mixture (anything richer than a mixture at the Rich Limit of flammability is irrelevant).

(2) The temperature of the richer mixture is at or above the self ignition temperature of the fuel.

(3) The chemical delay is no longer than the time taken for the reacting vapor to diffuse from the boundaries of the Rich to the Lean Limit of flammability.

In the present investigation, the fuel drops were evaporated as described earlier under ambient atmospheric pressure. The exposure of the drop to the atmosphere and the shape of the evaporating dishes in which fuel drops were being evaporated enhanced the efficient diffusion of the formed fuel vapor. This prevented the establishment of

the vapor concentration gradient described in condition
one. In addition, limiting the evaporating surface
temperature in this investigation to 500 degrees C pre-
vented the satisfaction of the second condition. As a
result, the spheroidal combustion did not occur in the
present investigation. It appeared, based on the above
postulate, however, that the surface temperature at which
spheroidal combustion may occur is dependent to a great
extent on the design of the experimental apparatus and on
the techniques used to heat the evaporating surface.

The ignition of the fuel drops was obtained, in
this investigation, in the form of intense and short flame
blow during the maximum rate of fuel evaporation. The
frequency of drop ignition in this mode was significantly
increased, when fuel additives and/or rough surfaces were
used to enhance the rapid vaporization of the fuel. In
view of the fact that the surface temperature at which
ignition occurred was substantially lower than the surface
temperature reported by Tamura and Tanasawa for spheroidal
combustion, it appeared that the experienced ignition was
mainly enhanced by the efficient and rapid vaporization of
the fuel that was obtained in this mode. The improvement
in the ignition characteristics of the fuel at such low
surface temperature certainly encouraged the utilization of
similar techniques to improve the vaporization, and the

combustion characteristics of fuels in a practical
combustion application.

## Evaporation Behavior of other Fluids

As was indicated earlier, the evaporation behavi.:
of no. 2 commercial diesel fuel and distillate water was
also examined during this investigation. The developed
evaporation curves for both the distillate water and the
diesel fuel are shown in Figures 9 and 10 respectively.
Both fluids displayed the same basic modes of evaporation
that were discribed earlier. The evaporation behavior of
the distillate water was very similar to that of the pure
fuels due to the uniformity of the water properties. The
evaporation lifetime of a water drop was substantially
longer than the lifetime of a comparable size fuel drop due
to the larger difference in the latent heat of vaporization
for the two liquids.

The evaporation behavior of no. 2 diesel was different
than that of a pure fuel especially in the contact and
spheroidal modes of evaporation. In the contact mode, the
fuel, since it contained several cuts of hydrocarbon went
through a pyrolysis process causing heavy and gummy
deposits to be left on the surface. It was very difficult
due to this liquid cracking to judge visually when the drop
was completely evaporated. The drop evaporation lifetime
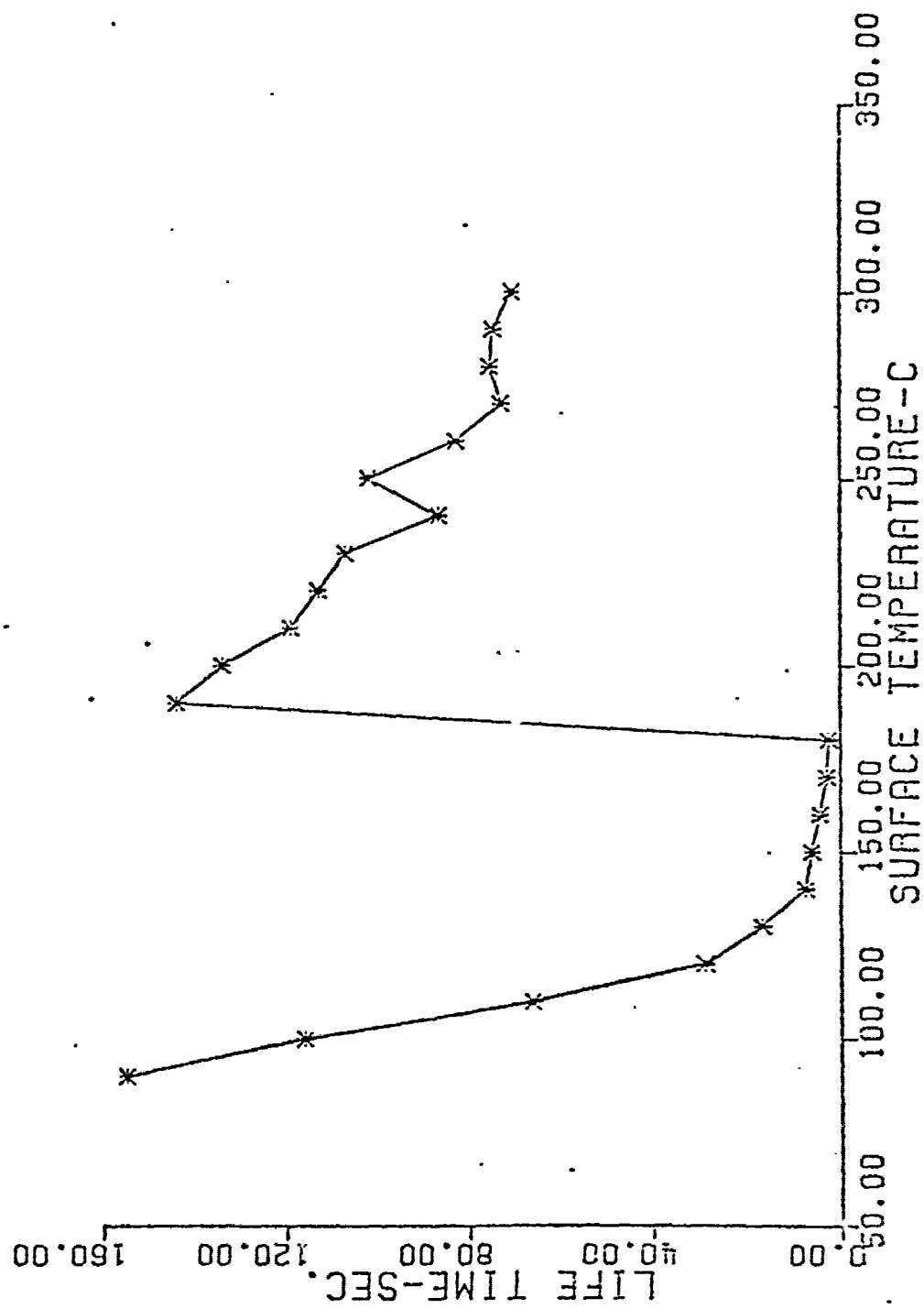
Figure 9. Evaporation lifetime of distillate water.
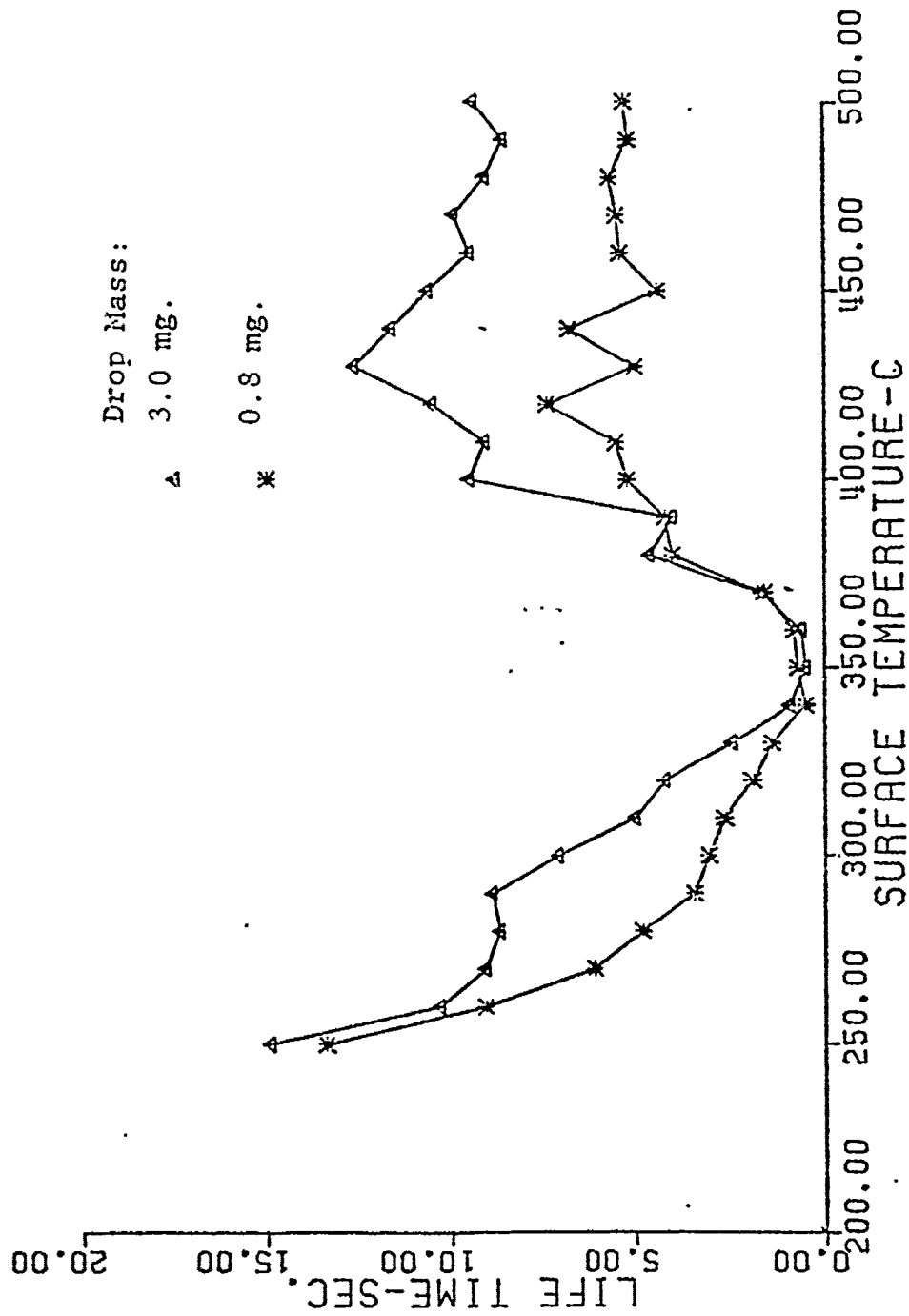
Figure 10.   Evaporation lifetime for no. 2 commercial diesel fuel.

was therefore recorded when all the light constituents evaporated, and only gummy deposits were left on the surface. The formed deposits were generally burned out after extended periods of time by heating to high temperatures and exposure to the atmosphere.

In the spheroidal mode, due to the difference in the boiling temperature of the various hydrocarbon cuts that are contained in the diesel fuel, the light fuel constituent evaporated instantly upon drop contact with the surface. When lifting into the spheroidal mode commenced, the formed fuel vapor became entrapped within the drop. As the drop evaporated, the entrapped vapor pocket expanded until the drop finally exploded like a balloon terminating its evaporation lifetime. The size of fuel drop when exploded was completely random in nature, and therefore significant fluctuation in the drop evaporation lifetime was generally experienced during this mode. As the surface temperature was progressively increased, the delay in drop lifting decreased reducing the size of vapor pockets formed within the drop, and resulting in an increase in drop evaporation lifetime.

## Effect of Evaporating Surface Design
### on Test Results

The effect of the evaporating surface design, on the

temperature range for the various modes of evaporation, was examined during this investigation in order to determine the applicability of the experimentally obtained test data to practical combustion applications. Acquiring such information was felt important, since previous investigators have used in conducting their experiments evaporating surfaces that are far different in quality than those generally encountered in a practical combustion apparatus. Identifying the effect of surface quality on drop evaporation behavior was justified by the need to understand the mechanism controlling the drop vaporization in the various modes.

Several types of evaporating surfaces were examined during the investigation. The surface variables that were evaluated included evaporating surface geometry, surface quality, interfacial surface tension between the fuel and the evaporating surface, and surface thermal conductivity. The effect of the studied variables on the drop evaporation was found to be as follows.

## Evaporating Surface Geometry

In reviewing the previous investigations, it was noted that all workers have machined a spherical depression of a certain geometry on the evaporating surface to prevent fuel drop from skidding off the surface. The degree by

which the geometry of these spherical depressions
influenced the result of the various investigators was not,
however, known. In view of the fact that the evaporation
curves developed in the present investigation were also
obtained using evaporating dishes of specific geometry, it
appeared of interest to determine the effect of the evapo-
rating surface geometry on the drop evaporation lifetime
for the various types of fuels.

Two stainless steel evaporating surfaces that have
substantially different geometrical configurations were
used in the evaluation. The first was the optimized evapo-
rating surface, manufactured with several evaporating dishes
machined on its surface. The second was a flat
stainless steel evaporating surface. Th evaporation
curves developed for n-Hexadecane and n-Heptane

using both evaporating surfaces are compared in Figures 11
and 12 respectively. The figures showed that a reduction
in drop lifetime in the contact and vaporization modes of
evaporation was achieved for both fuels when a flat surface
was used. This was mainly due to the increase in the
contact area between the drop and the surface that occurred
by allowing the drop to spread freely over the flat surface.
The reduction in the drop lifetime in the contact mode was
more significant in the case of n-Heptane due to the
relatively lower surface tension of the fuel. Allowing the
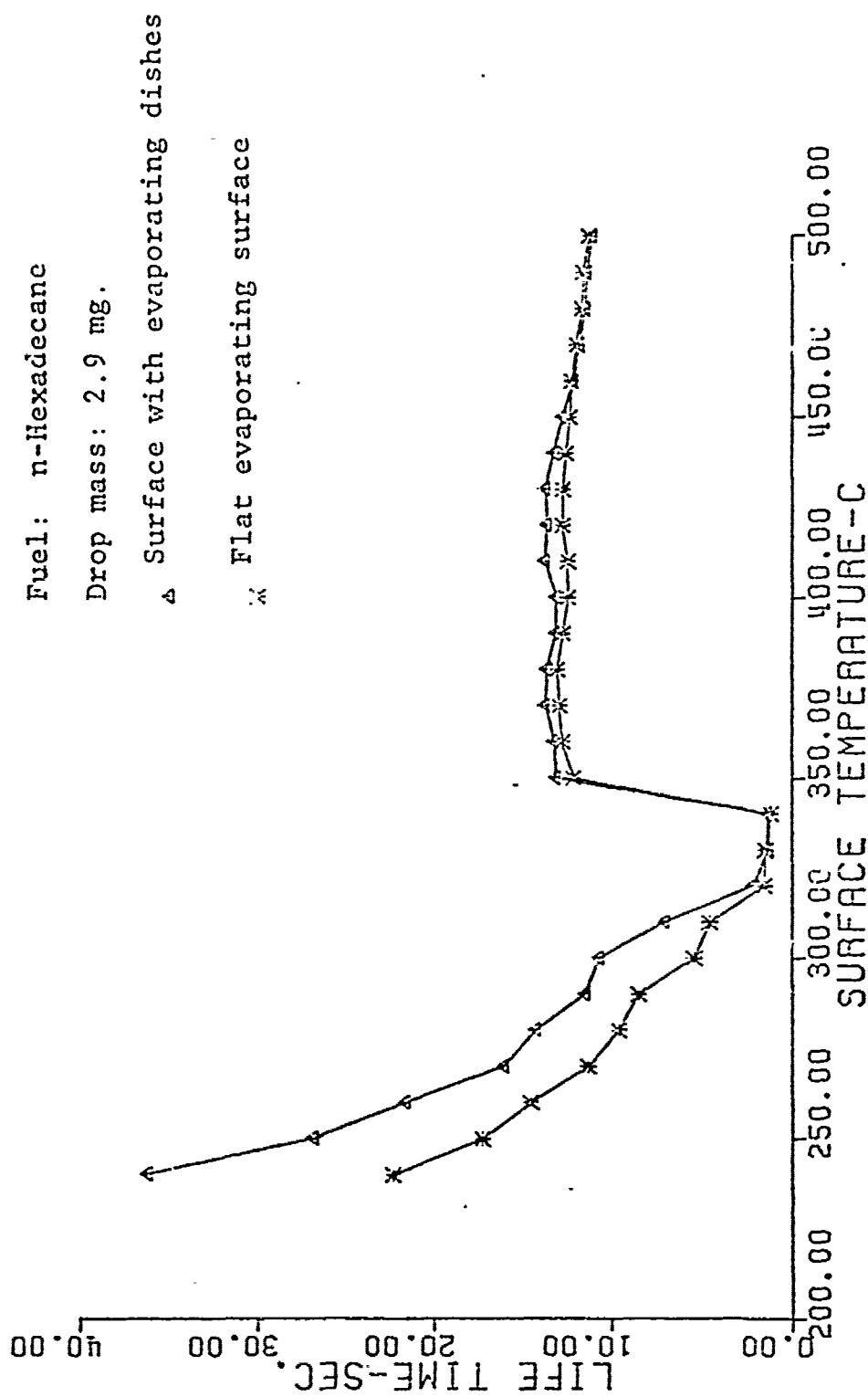
Figure 11.  Effect of evaporating surface geometry on the
evaporation lifetime of fuel drops.
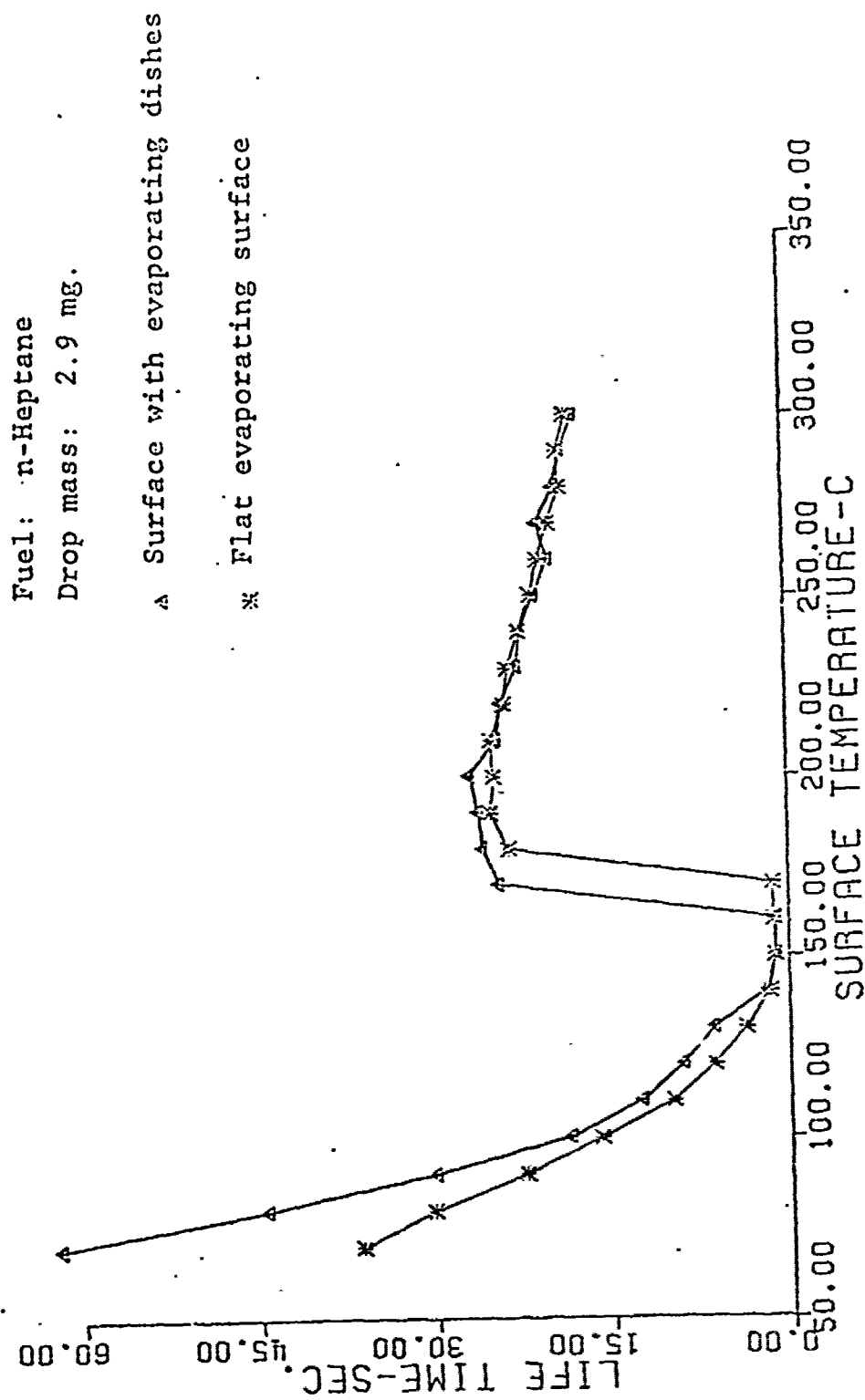
Figure 12.   Effect of evaporating surface geometry on the
evaporation lifetime of fuel drops.

fuel to spread rapidly over the flat surface also increased the surface temperature required for the spheroidal lifting of n-Heptane.

The fast spreading of the fuel drop over the surface increased the delay in drop lifting into the spheroidal mode. This increase in the delayed time caused a larger portion of the drop mass to evaporate before the spheroidal evaporation properly commenced, reducing the drop mass before lifting, and slightly reduced the drop evaporation lifetime in this mode. In the maximum evaporation rate mode, the surface geometry did not measureably affect the evaporation lifetime of the fuel drops.

To further emphasize the effect of evaporating surface geometry on test results, evaporation curves for 1-Octene, and pure distillate water were developed for the contact and vaporization modes using the two surfaces. The two fluids were selectively choosen due to the substantial difference in its surface tension. As can be seen from Figure 13 , no measureable reduction in evaporation lifetime was obtained for water when a flat evaporating surface was used. On the other hand, the reduction in lifetime for 1-Octene was as much as 60 percent especially at the beginning of the contact mode. The results clearly indicated that the influence of surface geometry on evaporating lifetime is different for the various types of fuels
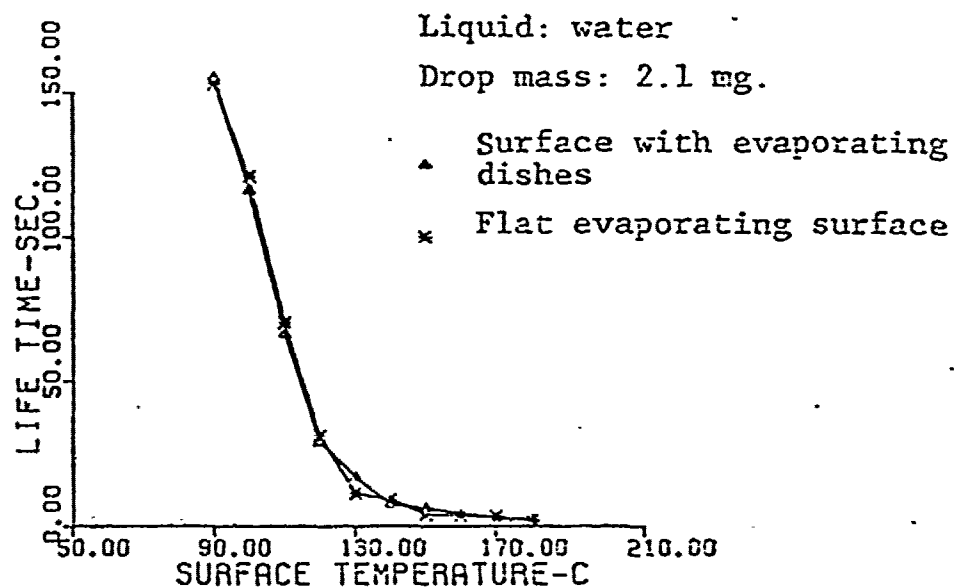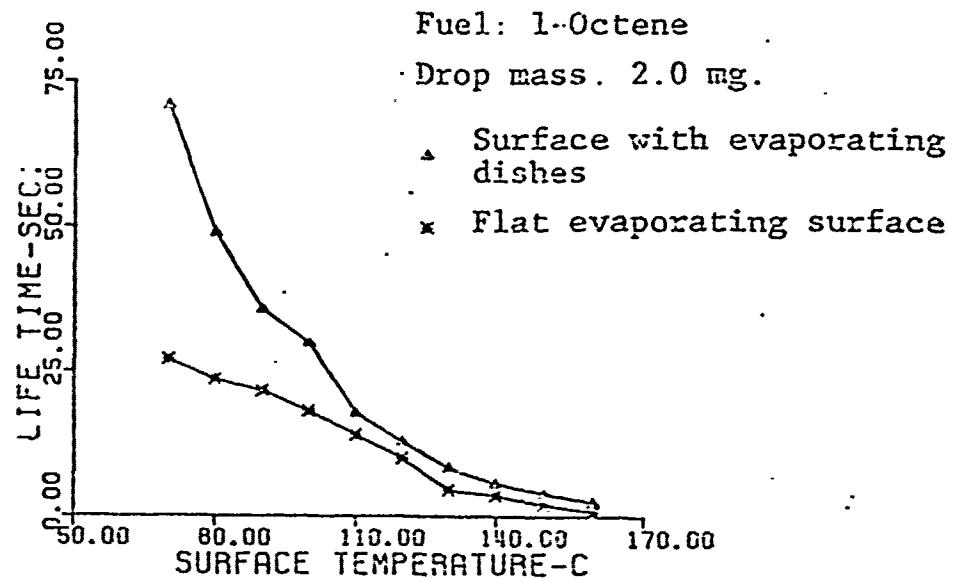
Figure 13. Effect of evaporating surface geometry on drop evaporation lifetime in the contact mode of evaporation.

and is mainly dependent upon the surface tension of the
fuel tested.

## Evaporating Surface Quality

As indicated earlier, previous investigators have used
evaporating surfaces of polished surface quality in
conducting their experiments. The obtained test results
were then compared by most investigators to the optimum
piston temperature reported by Meurer (1962). In light
of the fact that the quality of hot surfaces encountered
in practical combustion apparatus is quite different
from surfaces used by previous investigators, it appeared
of practical interest to evaluate the effect of the
evaporating surface quality on drop evaporation. To
achieve this objective, two rough evaporating surfaces
were used to examine the effect of surface roughness
on drop evaporation. Evaporation curves were also developed
using a stainless steel evaporating surface covered with
carbon and gummy deposits. The deposits were artifically
created by burning automotive lubrication oil on the
surface. The formed carbon deposits were rough and very
porous and resembled to some extent the surface quality
of a piston crown in a diesel engine.

The evaporation curves were developed on the two rough
surfaces for n-Heptane using two significantly different

drop sizes (2.5 mg and 0.45 mg). This was mainly done to
establish the degree by which surface roughness influences
the evaporation of drops of different sizes. The evapora-
tion curves were constructed by depositing the fuel drops
at the same location on the rough surface. The influence
of fuel residue left on the surface on drop evaporation
lifetime was felt in this case to be relatively minor
compared to the effect of surface roughness. The developed
evaporation curves were compared in Figure 14 and 15 to the
evaporation curves for the same size fuel drops developed
using polished evaporating dishes.

The figures clearly showed that a reduction in drop
evaporation lifetime in all modes of evaporation resulted
from the evaporation of the fuel drops on a rough surface.
In the contact mode of evaporation, for instance, the
reduction in drop lifetime was in the range of 60-80 percent
for both fuel drop sizes. The noted reduction in drop
lifetime in this mode was mainly attributed to the increase
in the contact area between the drop and the surface caused
by the surface roughness. This finding contradicted the
observations reported by Temple-Pediani (1969-1970) in
which he indicated that the surface roughness restricted
the spreading of the drop over the evaporating surface
resulting in an increase in drop evaporation lifetime. It
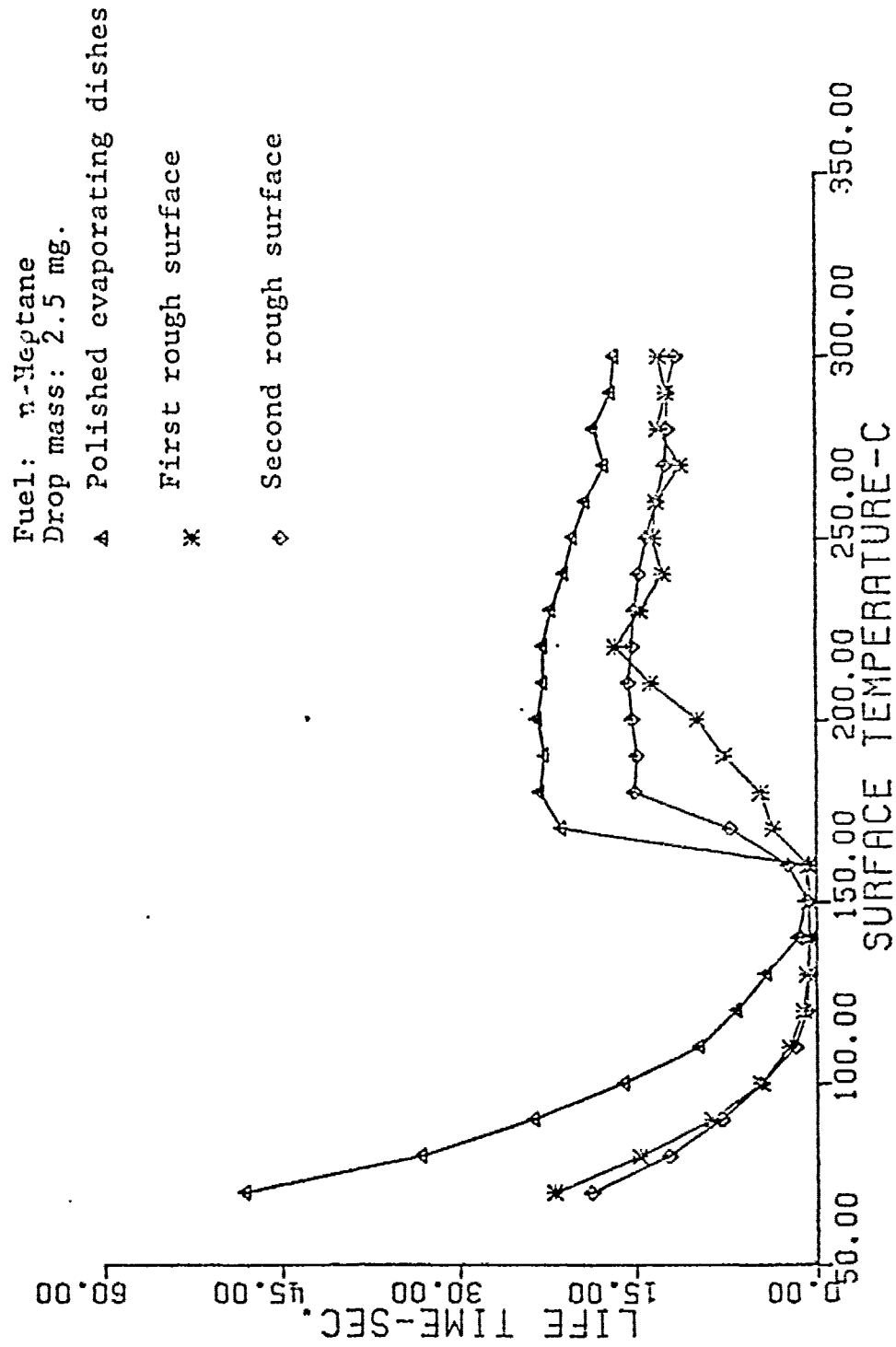
Figure 14.   Effect of surface roughness on drop evaporation.
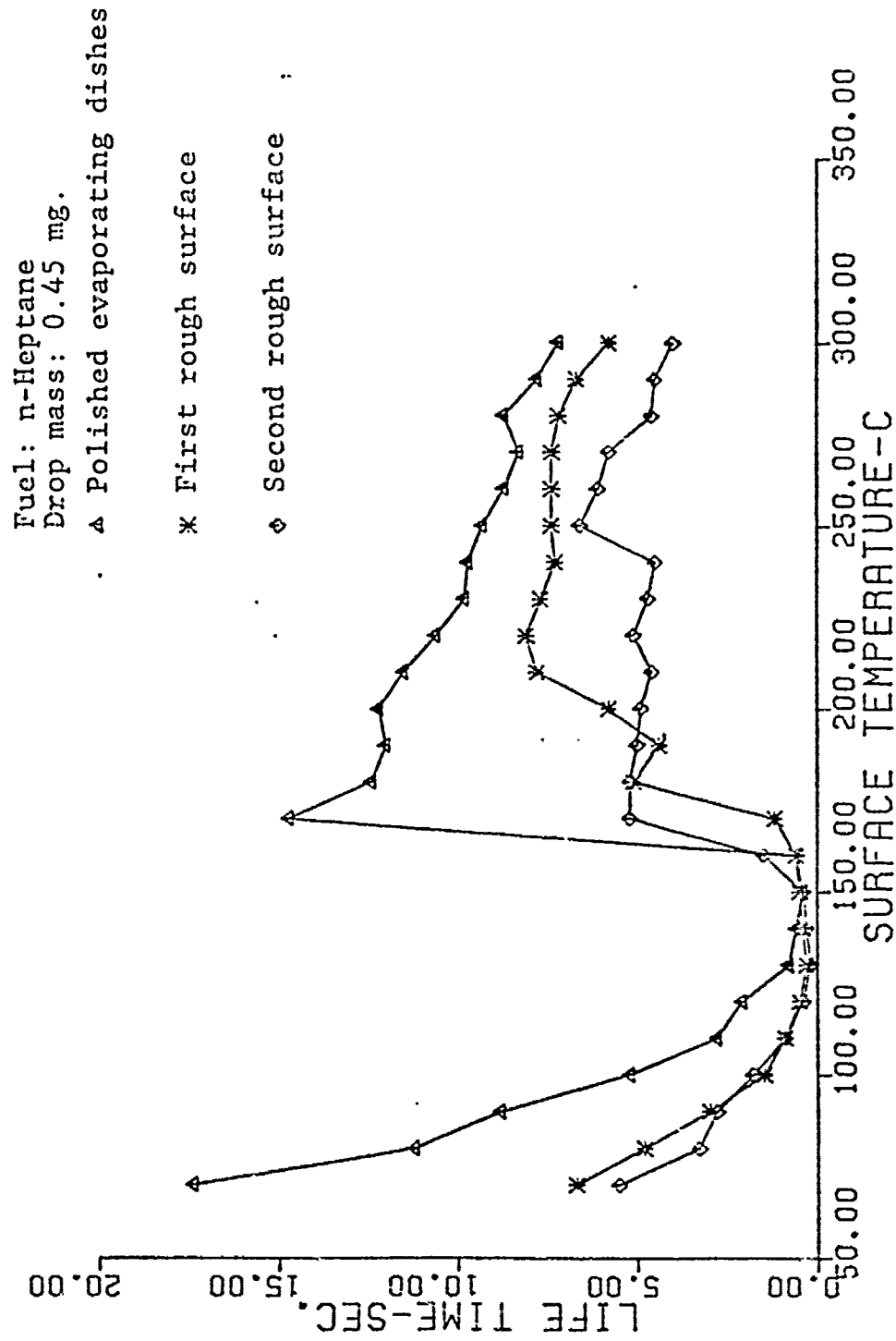
Figure 15.   Effect of surface roughness on drop evaporation.

appeared that the reason Temple-Pediani did not experience the substantial reduction in drop lifetime demonstrated in the present study was that the geometry and dimensions of the surface roughness used in conducting his experiment were not i· any way comparable in dimension to the fuel drops size used in the experiment. It is believed that the rough surfaces used in the present investigation, on the other hand, were fabricated to be proportional to the fuel drop size such that it resembled as closely as possible a scale up model of the fuel drop size and surface roughness that are normally encountered in a practical combustion apparatus. It is therefore felt that the results obtained in the present study relate more to the evaporation behavior of fuel drop in a practical combustion apparatus than the observation reported by Temple-Pediani.

In the maximum evaporation rate mode, the pock marks on the rough surface, acted as nucleation site for fuel boiling and significantly reduced the drop evaporation lifetime. Abrupt transition from the contact mode of evaporation to the maximum evaporation rate mode occurred with no indication displayed by the evaporation curve for the vaporization mode of evaporation. The surface roughness reduced the temperature at which the maximum evaporation rate mode began by more than 40 degrees C and expanded the temperature range over which this mode of evaporation

prevailed.

The transition mode, that was referred to and discussed by previous investigators, was clearly displayed by the evaporation curves developed using rough surfaces. The occurrence of such mode was related essential to the increase in the delay time in drop lifting off the surface into the spheroidal evaporation. The temperature range over which the transition mode prevailed was strictly dependent upon the physical restriction offered by the rough surface to delay or prevent the lifting of the fuel drop. This temperature range was as a result wider for the first rough surface due to the large number of grooves per unit area that are machined on the surface. As the surface tempera- ture was progressively increased, the delay in drop lifting decreased which reflected a corresponding increase in drop evaporation lifetime.

In the spheroidal mode, the noted reduction in drop lifetime was also caused by the increase in the delay of drop lifting off the surface. After the drop was lifted off the surface, however, the larger the grooves volume under- neath the drop, the closer was the drop to the rough peaks of the surface. The drop evaporation lifetime for the second rough surface were as a result shorter than for the first surface, especially for the small size fuel drops where the volume of vapor generated from the drop was rather

small compared to the grooves volume. The severe fluctua-
tion in evaporation lifetime in this mode was strictly due
to the random change in the delay of drop lifting.

To determine the effect of gummy carbon deposits on
the evaporation of the fuel drops, the evaporation curve for
n-Heptane developed on polished evaporating dishes was
compared in Figure 16 to the evaporation curves for same
fuel and for the same size fuel drop developed on a stain-
less steel surface covered with carbon deposits. As can be
seen from the figure, a substantial reduction in drop
evaporation lifetime was obtained by evaporating the fuel
drops on the carbon surface. The reduction in the drop
lifetime was mainly noted in the contact, vaporization, and
spheroidal mode of evaporation. A slight increase in
evaporation lifetime occurred within the temperature range
for the maximum evaporation rate mode due to the insulation
effect of the carbon layer. The maximum evaporation rate
mode occurred on the carbon surface at a slightly higher
surface temperature, and drop evaporation continued in this
mode during the surface temperature range for the
spheroidal evaporation. The lifting into the spheroidal
mode did not occur using the evaporating surface covered
with carbon deposits due to the high "affinity" of the fuel
to the surface. The fuel drop rather than being lifted on
a vapor cushion, it gathered itself up upon contact with
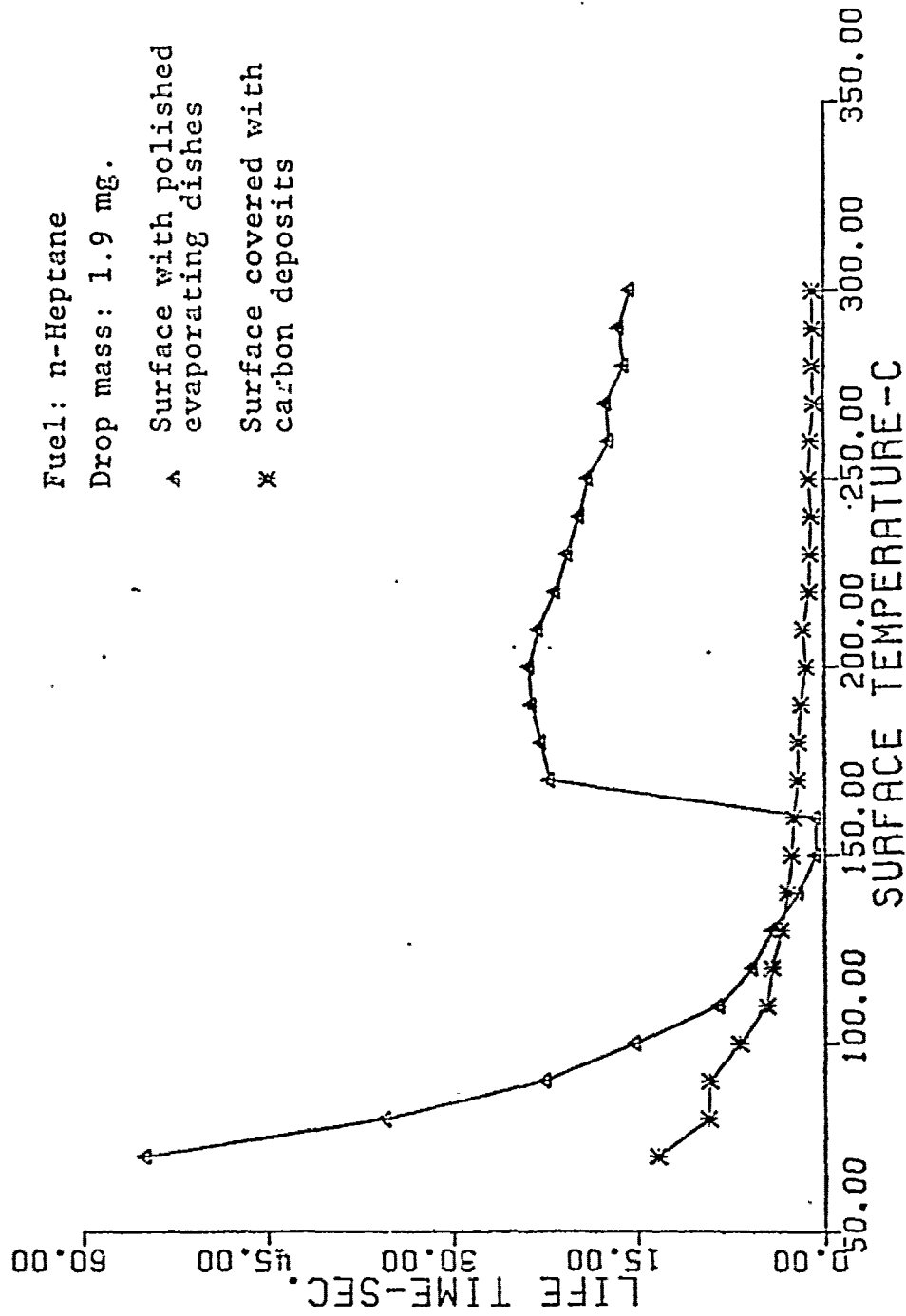
Figure 16.   Effect of carbon deposits on the evaporation
lifetime of fuel drops.

Fuel: n-Heptane

Drop mass: 1.9 mg.

▲   Surface with polished
evaporating dishes

*   Surface covered with
carbon deposits

SURFACE TEMPERATURE-C

LIFE TIME-SEC.

the surface into a part sphere but the drop remained,
however, in contact with the surface. As the liquid
temperature was raised, the drop collapsed with vapor mass
transfer continuously increasing, creating a dense vapor
cloud over the drop. The lifetime of the drop remained
during a wide temperature range a constant minimum and
independent of the surface temperature.

In view of the fact that in most applications, the
wall of the apparatus is generally covered with heavy
carbon deposits, it appears based on the above test results,
that maintaining the apparatus wall temperature at suffi-
ciently high level will insure the rapid vaporization of the
deposited fuel drops for a wide range of surface tempera-
tures. The finding alleviated the concern expressed by
previous investigators regarding the impracticality of
maintaining the wall of a combustion apparatus within the
narrow temperature range identified for the maximum evapo-
ration mode. In light of the above test results, it is
believed that the difference that existed between the
optimum piston temperature obtained by Meurer using the
M-combustion system of MAN, and the surface temperature for
the maximum evaporation rate mode that was experimentally
determined by Temple-Pediani under supercritical conditions
of pressure and temperature was merely caused by the
substantial difference in the surface quality used by the

investigators.

## Surface Tension between the Fuel and
### the Evaporating Surface

The area of contact between a fuel drop and an
evaporating surface is predominantly controlled by the fuel
surface tension and by the interfacial surface tension
between the fuel and the evaporating surface. In view of
the fact that the drop evaporation lifetime in all modes of
evaporation is very dependent upon this contact area, it
appeared of interest to study the effect of the interfacial
surface tension between the fuel and the surface on drop
evaporation lifetime.

Two flat evaporating surfaces (stainless steel and
aluminum) that were coated with a very thin layer
of Dow Corning Pan Shield were used in the
evaluation. Evaporation curves were developed for
n-Heptane using the stainless steel and aluminum surfaces
before and after the application of the surface coating and
the obtained curves were compared in Figures 17 and 18
respectively. As can be seen from the figures, reducing
the interfacial surface tension between the fuel and the
surfaces enhanced fuel spreading over the surfaces which in
turn reduced the drop evaporation lifetime in all modes of
evaporation. The fast spreading of the fuel drops delayed
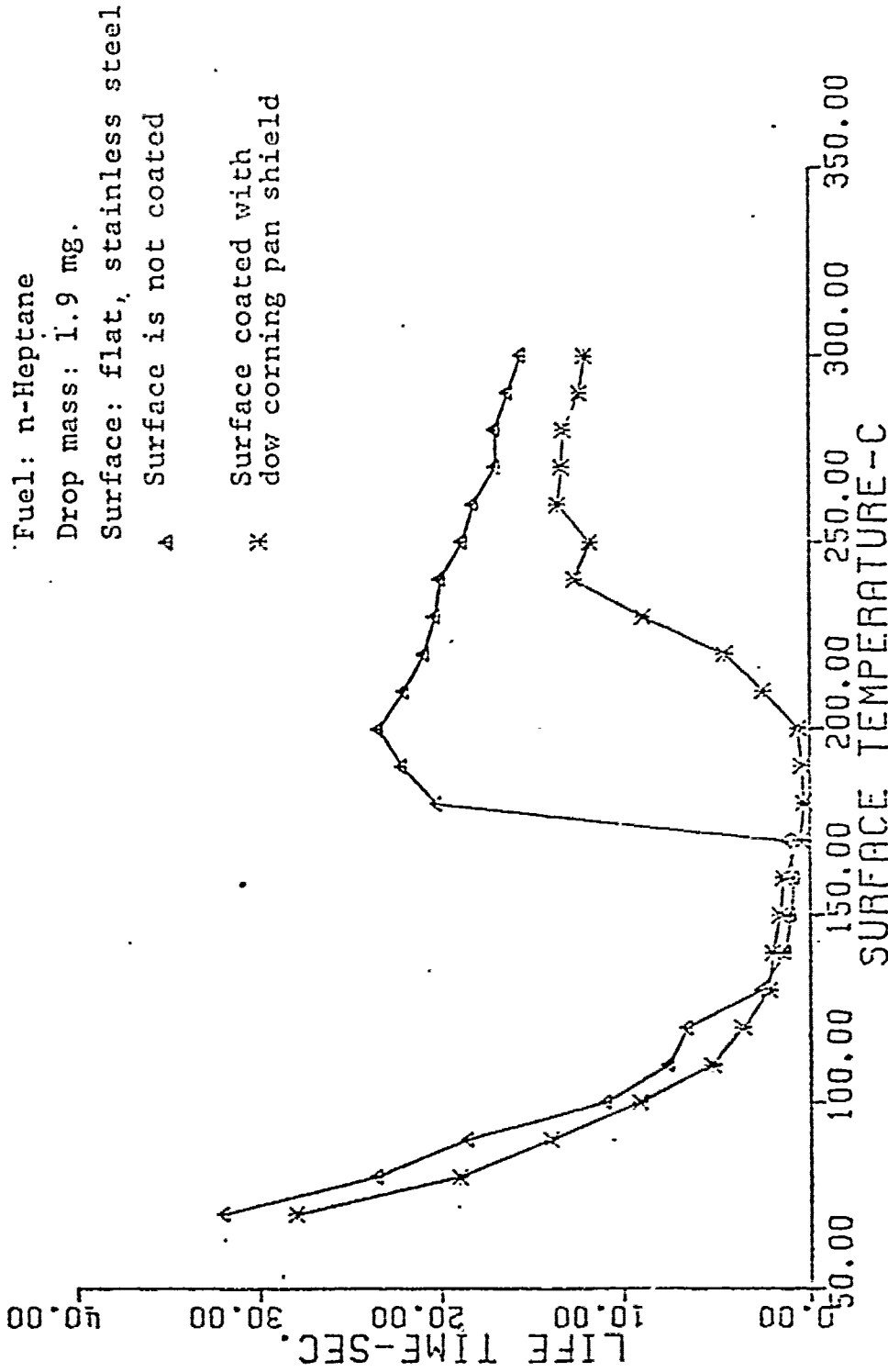
Figure 17. Effect of the surface tension between the fuel and the evaporating surface on drop evaporation lifetime.

58
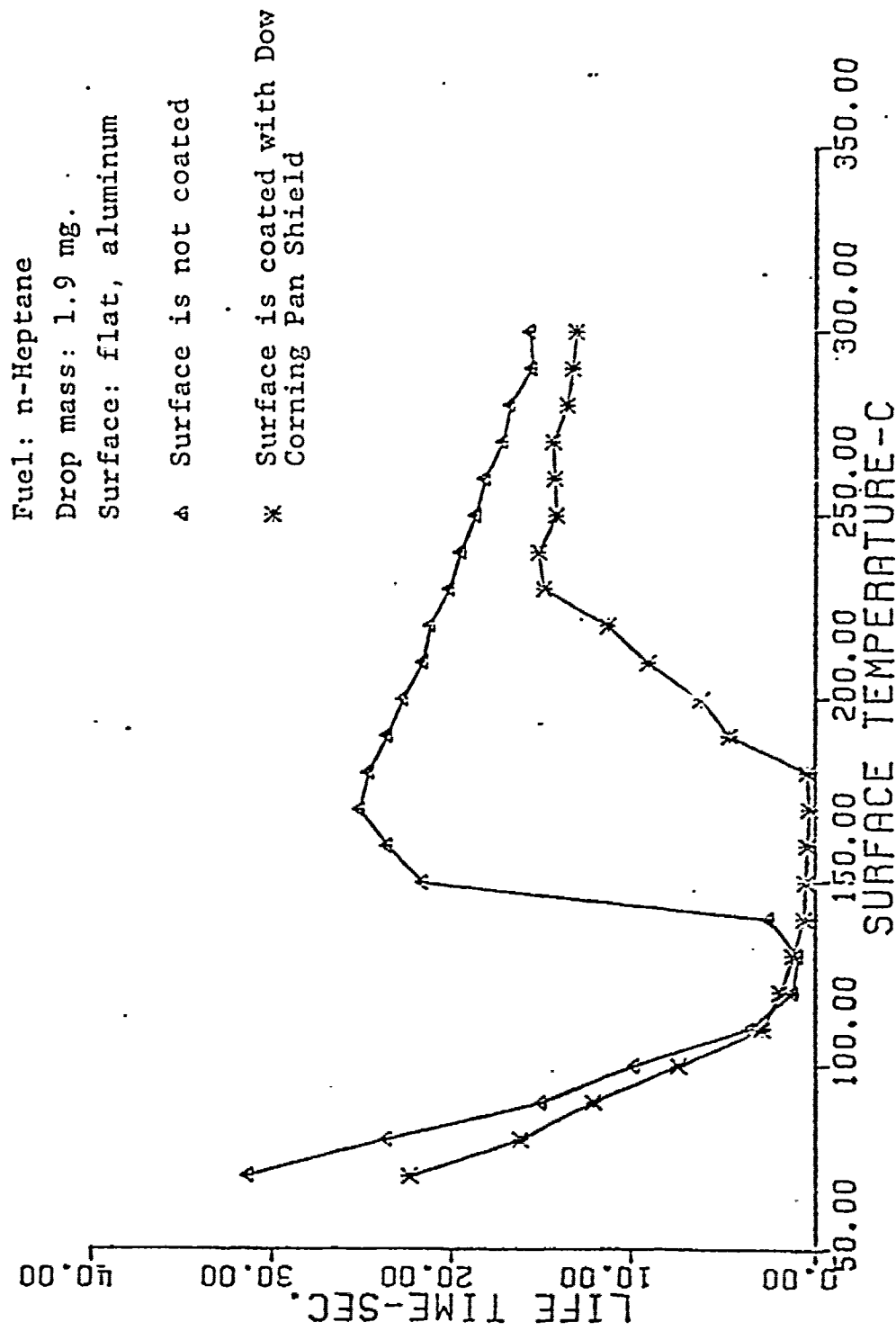


Figure 18.  Effect of the surface tension between the fuel and the evaporating surface on drop evaporation lifetime.

the occurrence of the spheroidal evaporation and expanded
the temperature range over which the maximum evaporation
rate mode prevailed. The delay in drop lifting into the
spheroidal mode achieved by the low surface tension
between the fuel, and the surface, caused a larger portion
of the drop to evaporate before the drop lifting occurred,
and resulted in a substantial reduction in drop evaporation
lifetime in this mode. As can be noted from the figures,
the delay in spheroidal lifting progressively decreased as
the surface temperature increased causing a corresponding
increase in the evaporation lifetime. The slight overlapping
of the evaporation curves developed before and after the
application of the surface coating in the maximum evapo-
ration rate mode was mainly attributed to the insulation
effect introduced by the coating layer. The insulation
effect of this layer of coating was only noticeable during
this mode of evaporation due to the high intensity of the
heat flux that is transferred to the drop.

Expanding the temperature range over which the
maximum evaporation rate mode takes place has a definite
practical value. Based on the above test results, the
temperature range within which the walls of a combustion
apparatus should be maintained could be more than doubled
if appropriate coating was applied to these surfaces. An
immediate practical application for such approach for

example will be the coating of the inlet manifold of a
spark ignition engine with "Teflon" or similar material
to reduce the interfacial surface tension between the fuel
and the surface. Applying such coating in the appropriate
locations may enhance the vaporization of fuel drops
deposited on the manifolds walls and improve the uniformity
of the mixture quality that is introduced to the various
cylinders.

## Evaporating Surface Thermal Conductivity

The effect of the evaporating surface thermal conduc-
tivity on the drop evaporation lifetime was evaluated using
two flat surfaces; one from stainless steel and the other
from aluminum. Evaporation curves were developed for
n-Heptane using the same size fuel drop with both surfaces
and the obtained evaporation curves were compared in
Figure 19 . By examining the figure it is quite evident that
the use of an aluminum surface caused drop lifting into the
spheroidal mode to occur at a surface temperature 20 degrees
C lower than that for the steel surface. This was mainly
due to the high thermal conductivity of the aluminum surface
which significantly dampened the effect of the intense
localized surface cooling introduced by the drop on the
surface prior to its lifting. Causing spheroidal lifting to
occur early, however, slightly narrowed the temperature
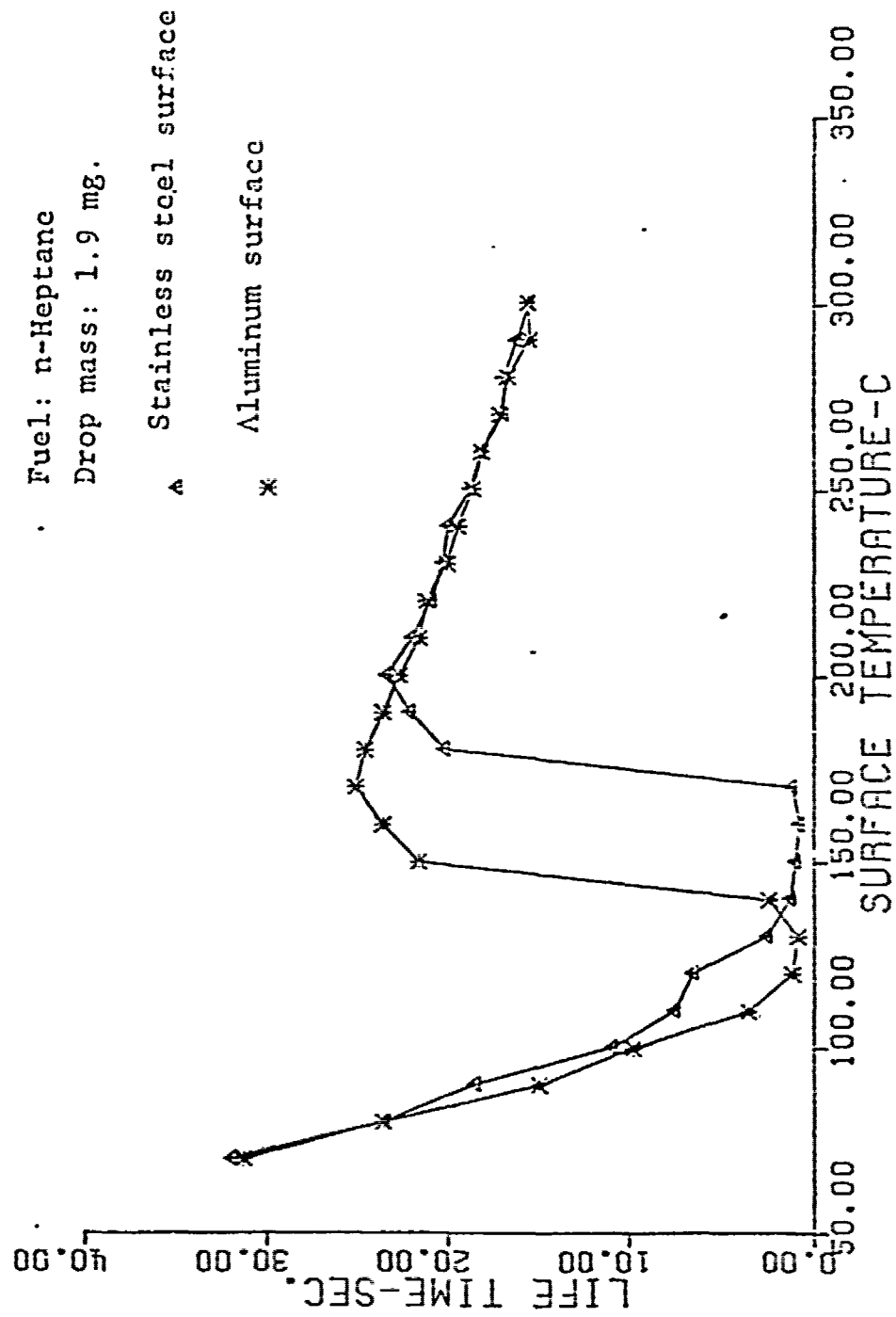
Figure 19. Effect of evaporating surface thermal conductivity on drop evaporation lifetime.

range for the vaporization and maximum evaporation rate
modes. The evaporation lifetime in the spheroidal mode
was not in any way affected by the thermal characteristics
of the evaporating surface due to the insulation effect of
the vapor cushion that is formed underneath the drop in
this mode.

It seems advantageous, based on the above results to
manufacture the walls of combustion apparatus that are
exposed to excessively high temperature level from poor
thermal conducting material. Upon drop impingement on
these surfaces, the intense localized surface cooling
introduced by the deposited fuel drop may be sufficiently
severe to "locally" reduce the surface temperature, and
cause the drop to evaporate in the maximum evaporation rate
mode rather than in the spheroidal mode of evaporation.

## Effect of Fuel Properties on Test Results

It is generally agreed by previous investigators
that it is not practical to maintain the walls of a
combustion apparatus within the narrow temperature
range identified for the maximum evaporation rate mode.
In spite of the demonstrated advantages of operating
the combustion apparatus within this temperature
range, the practical limitations implied by the test
results were accepted by most investigators without

question. The surface temperatures at which
·transition from one mode of evaporation to another occurred
was correlated by most investigators, only to the boiling
temperature of the fuel. The effect of other fuel
properties on drop evaporation remained as a result to a
great extent obscured.

In light of the need·to expand the temperature
range over which the maximum evaporation rate mode occurs,
it was required to accurately define the effect of fuel
propertie. on the surface temperature range for the various
modes. Extensive refinement of the experimental apparatus
was .initially required, as described earlier, in order to
minimize the effect of apparatus variables on the test
resul⁺s and further amplify the influence of the fuel
properties on the evaporation behavior of the drop. The
effect of fuel properties on drop evaporation in the
various modes was closely examined upon achieving the
desired level of experimental accuracy. Fuel properties
that influenced or controlled the surface temperature range
within which the various modes of evaporation occurred
were successfully determined. The mechanics by which fuel
additives brought about an improvement in the combustion
quality of the fuel in the various combustion applications
were also qualitatively evaluated. Fuel properties that
were examined during the investigation included fuel

boiling temperature, surface tension, fuel partial vapor pressure as a function of its temperature, latent heat of vaporization, and specific heat. The effect of the examined properties on drop evaporation was found to be as follow...

## Fuel Boiling Temperature

The surface temperature at the transition bet een the various modes of evaporation were recorded in the present investigation for a variety of pure fuels and for water. These surface temperatures were determined when the drops were evaporated on the optimized evaporating surface that has polished evaporating dishes machined on its surface. The identified surface temperature for the various liquids are presented in Table 1.

By comparing the boiling temperature of the tested fuels to the surface temperature at the transition between the various modes in Figure 20, it was noted, that a linear relationship existed for each mode of evaporation between the boiling temperature of the fuel and the surface temperature at the beginning of this mode. The results supported findings of previous investigators which emphasized that a strong relationship exists between the temperature range within which the various modes of evaporation occur and the fuel boiling temperature. By further examining Figure 20,

## TABLE 1

### SURFACE TEMPERATURE AT WHICH DIFFERENT
### MODES OF EVAPORATION OCCURRED

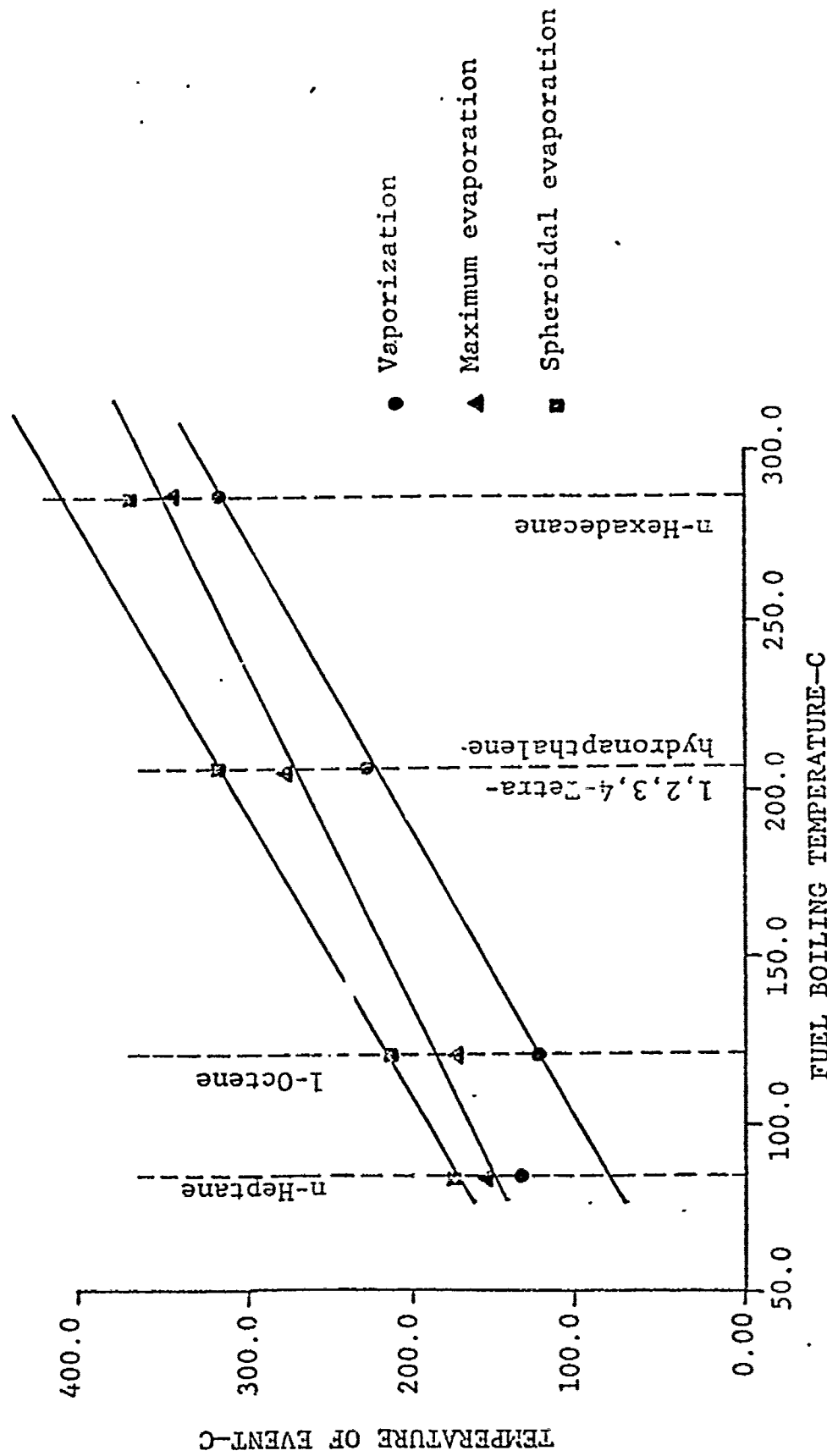| Type of Fuel | Boiling Temperature | Surface Temperature in Degrees C at the Beginning of the Various Modes | | |
|---|---|---|---|---|
| | | Vaporization Mode | Maximum Evaporation Mode | Spheroidal Mode |
| n-Heptane | 98.42 | 130 | 150 | 170 |
| 1-Octene | 121.6 | 120 | 170 | 210 |
| 1,2,3,4-Tetrahydro-naphthalene | 205.8 | 220 | 270 | 310 |
| n-Hexadecane | 286.5 | 310 | 340 | 350 |
| Distillate water | 100. | 140 | 170 | 190 |

66



Figure 20.  Relationship between the fuel boiling temperature
and surface temperature at the beginning of the
various modes of evaporation.

it was noted, however, that a deviation off the straight
line relationship was quite evident in two locations on the
graph; for n-Heptane off the straight line for the vapori-
zation mode and for n-Hexadecane off the straight line for
the spheroidal mode. It could be generally argued that the
deviation of these two points off the straight line rela-
tionship is merely a scatter in the experimental data. By
examining the fuel properties presented in Table 2, it was
felt, however, that such deviation could very well be ex-
plained by the effect of fuel properties on drop evapo-
ration. For the n-Heptane, for example, the fuel latent
heat of vaporization was relatively high compared to its
boiling temperature. In addition, its high surface tension
compared to 1-Octene did not encourage the efficient sprea-
ding of the drop over the surface. Both factors are believed
to have resulted in having the vaporization mode    occur at
a higer surface temperature. For n-Hexadecane, the fuel low
latent heat of vaporization coupled with its relatively high
surface tension caused the spheroidal mode of evaporation
to occur at a lower temperature level. By comparing the
surface temperature for the various modes of evaporation
for water, and n-Heptane in Table 1 it was also noted that
although the two liquids for all practical purposes have
essentially the same boiling temperature, the surface tem-
perature at the beginning of the various mode for the two

## TABLE 2

### PROPERTIES OF TESTED FUELS*

| Type of Fuel | Specific Gravity 20/4 C | Boiling Temp. Deg. C | Specific Heat | Heat of vapori-zation Cal/c | Surface Tension 20 Deg. C |
|---|---|---|---|---|---|
| n-Heptane | 0.68808 | 98.42 | 0.525 | 76.1 | 20.26 |
| 1-Octene | 0.7150 | 121.6 | 0.486 | 71.7 | 12.62 |
| 1,2,3,4- Tetra- hydronaph- thalene | 0.9707 | 206.8 | 0.403 | 79.1 | 34.34 |
| n-Hexadecane | 0.77335 | 286.5 | 0.495 | 41.9 | 27.66 |
| Distillate water** | 1.0 | 100.0 | 1.0 | 100.10125 | 72.76 |

*M. P. Doss (1942)
**R. H. Perry (1973)

fluids was substantially different. The surface temperature for water at the beginning of the maximum evaporation rate mode and the spheroidal mode for example was 20 degrees C higher than that for n-Heptane. For the vaporization mode, the surface temperature for water was again 10 degrees C higher than that for n-Heptane. It appeared that a higher surface temperature was required to initiate the various modes of evaporation for water mainly because of its higher latent heat of vaporization.

It should be pointed out that the linear relationship between the boiling temperature of the fuel and surface temperature at the beginning of the various modes presented in Figure 20 holds only for the evaporation of the fuel drops on an evaporating surface of a polished surface quality. Using evaporating surfaces of different geometry, surface material, and/or surface quality will substantially change these surface temperature values. It will be also demonstrated later in this investigation that doping the tested fuels by a small fraction (1-3 percent) of fuel additives to reduce its surface tension could increase the surface temperature required for the spheroidal lifting by more than 50 degrees C. In view of the fact that the fuel additives were blended with the tested fuel in very small proportions, it is believed that the fuel boiling temperature did not change and the

increase in the surface temperature required for the
spheroidal evaporation was mainly caused by the reduction
in fuel surface tension.

It is concluded based on the above results that a
straight line relationship may exist between the fuel
boiling temperature and the temperature at the beginning of
the various modes of evaporation for most of pure hydro-
carbon fuels. The straight line relationship is generally
obtained when the fuel drops are evaporated on a polished
evaporating surface. Deviation off the straight line
relationship would occur, however, if the fuel was selecti-
vely chosen to have a high latent heat of vaporization and
specific heat coupled with a low surface tension.

The rate of the decrease in the evaporation lifetime
of the fuel drops with respect to the increase in the
surface temperature was found, in the spheroidal mode, to
be dependent upon the boiling temperature of the fuel.
Approximating the relationship between the drop evaporation
lifetime and the surface temperature in the spheroidal mode
by a straight line clearly indicated that the slope of the
line progressively increased as the boiling temperature of
the fuel decreased. To examine the change in the slope of
this line with the boiling temperature of the fuel qualita-
tively, experimental data for the spheroidal mode of evapo-
ration for three different types of fuels (n-Heptane,

1-Octene, and n-Hexadecane) were fitted with the last square fit to the straight line approximation. It was found, as shown in Figure 21 that the slope of the fitted straight line progressively increased from 0.0214 to 0.0830 with the decrease in the boiling temperature of the fuel form 286.5 degrees C to 98.4 degrees C. A larger reduction in drop evaporation lifetime occurred for the same incremental increase in the surface temperature for fuels of low boiling temperature since spheroidal lifting for these fuels also occur at a lower surface temperature. The percent increase in the surface temperature for the same temperature increment was as a result higher for fuels of low boiling temperature than for fuels of high boiling temperature.

It seems appropriate to also point out at this time that the slope of the line for spheroidal evaporation is also influenced by the thermal conductivity of the fuel vapor and by thickness of the vapor cushion formed underneath the drop. The effect of these two variables have not been quantitatively identified in the present study and therefore it definitely merits consideration for future investigation.

## Fuel Surface Tension

The effect of fuel surface tension on the evaporation behavior of the drops was examined by doping the tested
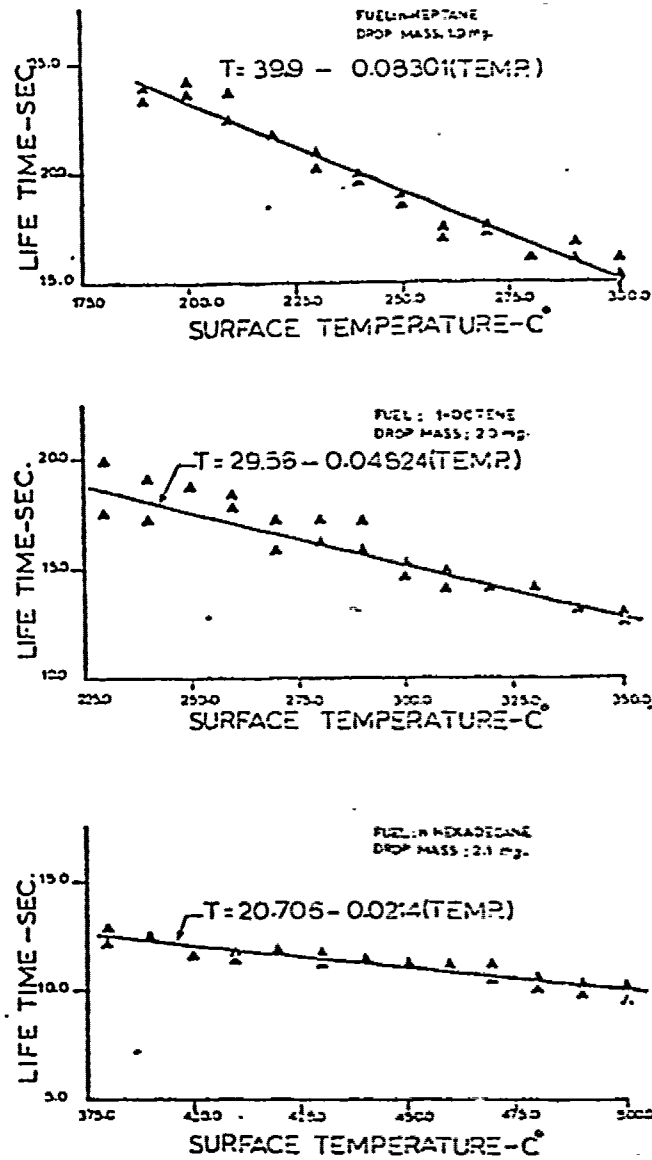
Figure 21.  Decrease in drop evaporation lifetime in the spheroidal mode with respect to the increase in the surface temperature.

fuels with special additives to reduce its surface tension.
The used additives were manufactured by Chevron Research
Company and carried the following commercial names:

CR-75R-5382, OGA, Ashless Amine Dispersant

CR-75R-5383, OFA Polysneric, Succinimide Dispersant

CR-75R-5384, OLOA 246A, Calcium sulfonate

CR-75R- 5385, OLOA 211, Sulfuric Calcium Phenate.

The additives were blended with the fuels in
volumetric proportion and the blend ration was maintained
sufficiently low to insure that other fuels properties
remain unchanged. The additives used will be referred to
in the text and on the graph by their numbers for
abbreviation.

Evaporation curves for n-Heptane, 1-Octene, and
1,2,3,4-Tetrahydronaphthalene were developed when the fuels
were blended with 3 percent by volume of CR-75R-5382 fuel
additive. The developed evaporation curves were then
compared in Figures 22 through 24 with the evaporation
curves for the pure fuels. The figures clearly showed that
reducing the fuel surface tension enhanced drop spreading
over the evaporating surface and resulted in a reduction in
drop evaporation lifetime in all modes of evaporation. The
largest reduction in drop lifetime was generally experien-
ced in the spheroidal mode. This was again due to the
increase in the delay of drop lifting off the surface into

74



Figure 22.  Effect of fuel surface tension on drop evaporation lifetime.

Fuel: 1-Octene

Drop mass: 2.0 mg.

△ Pure fuel

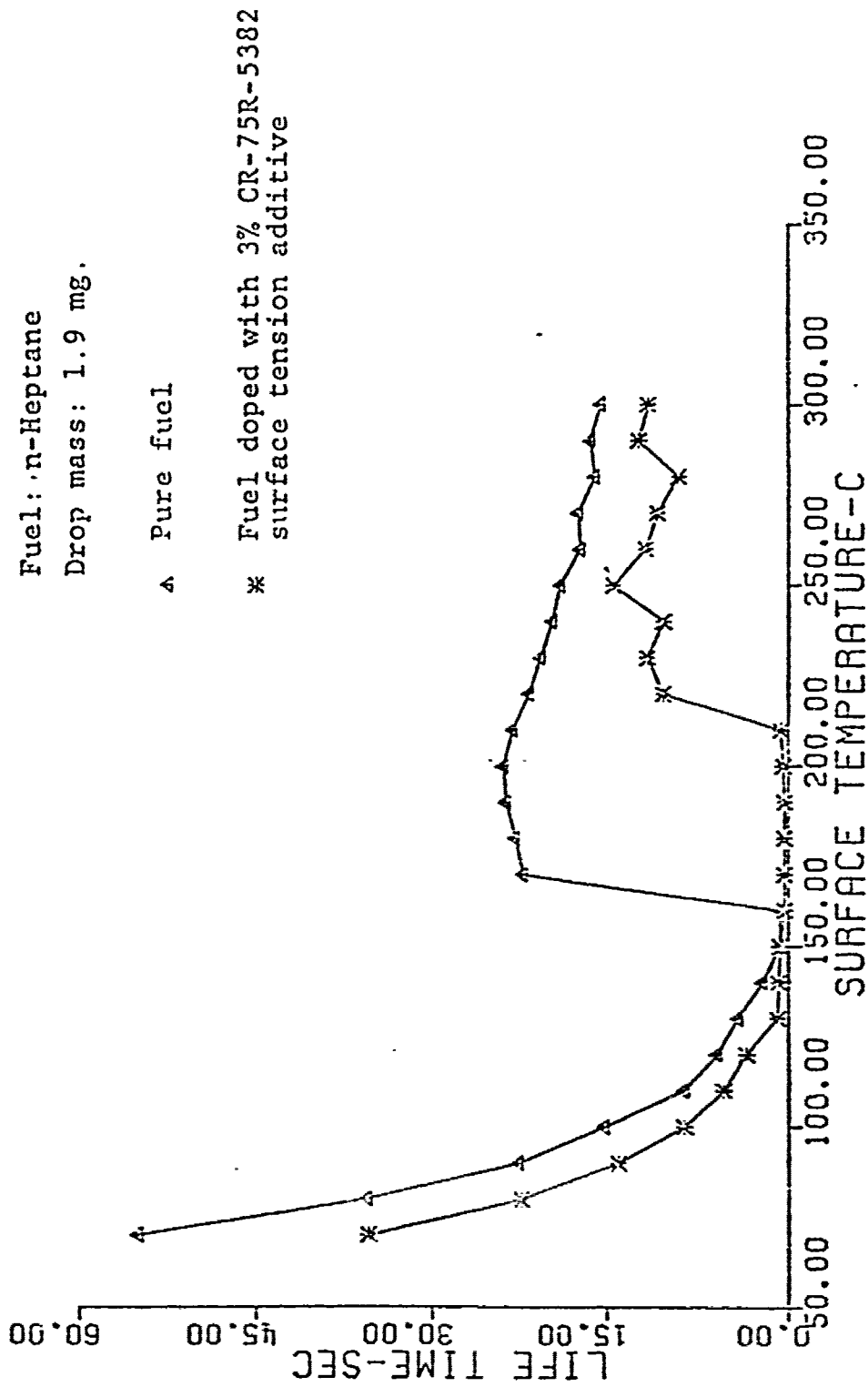✳ Fuel doped with 3% CR-75R-5382
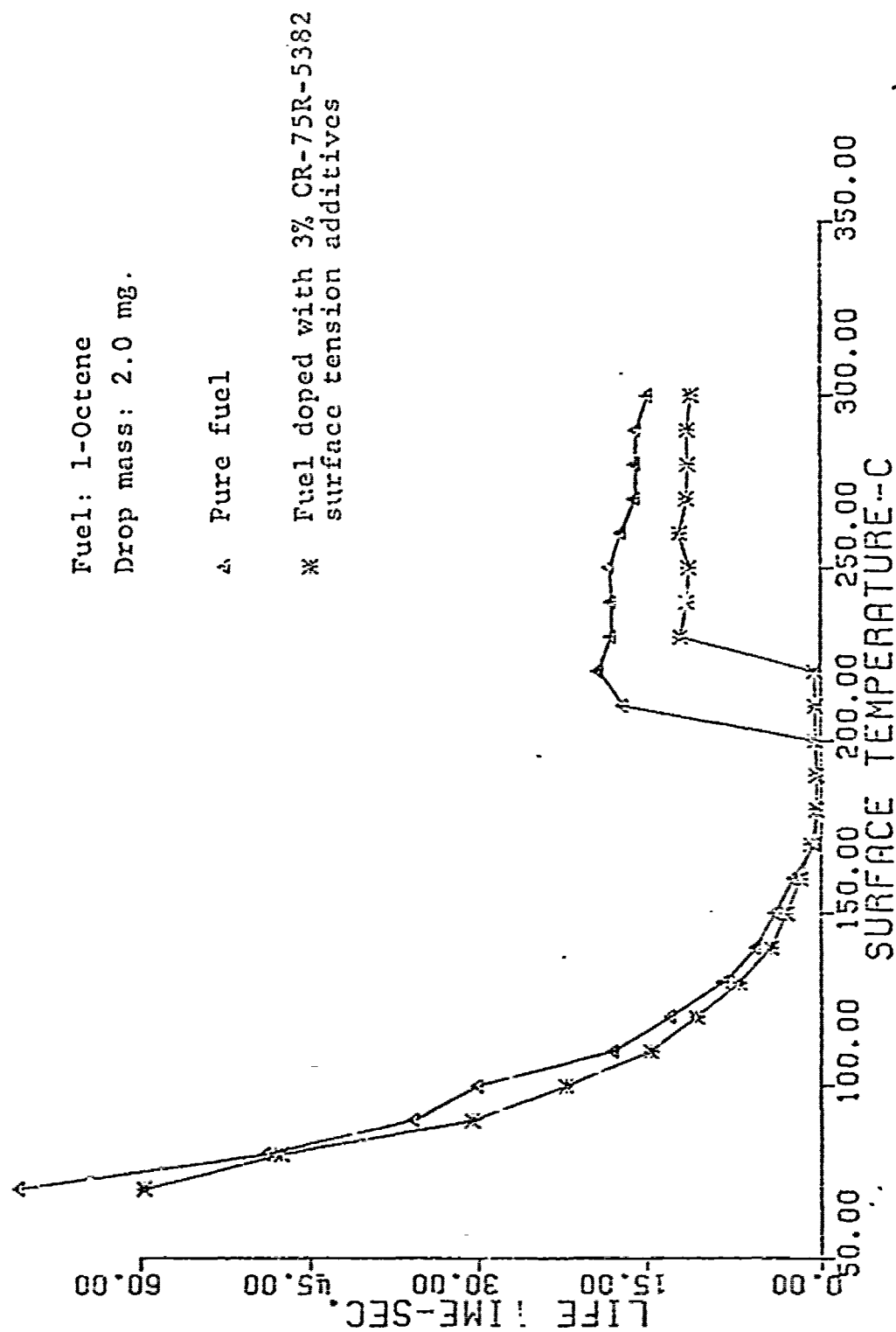surface tension additives

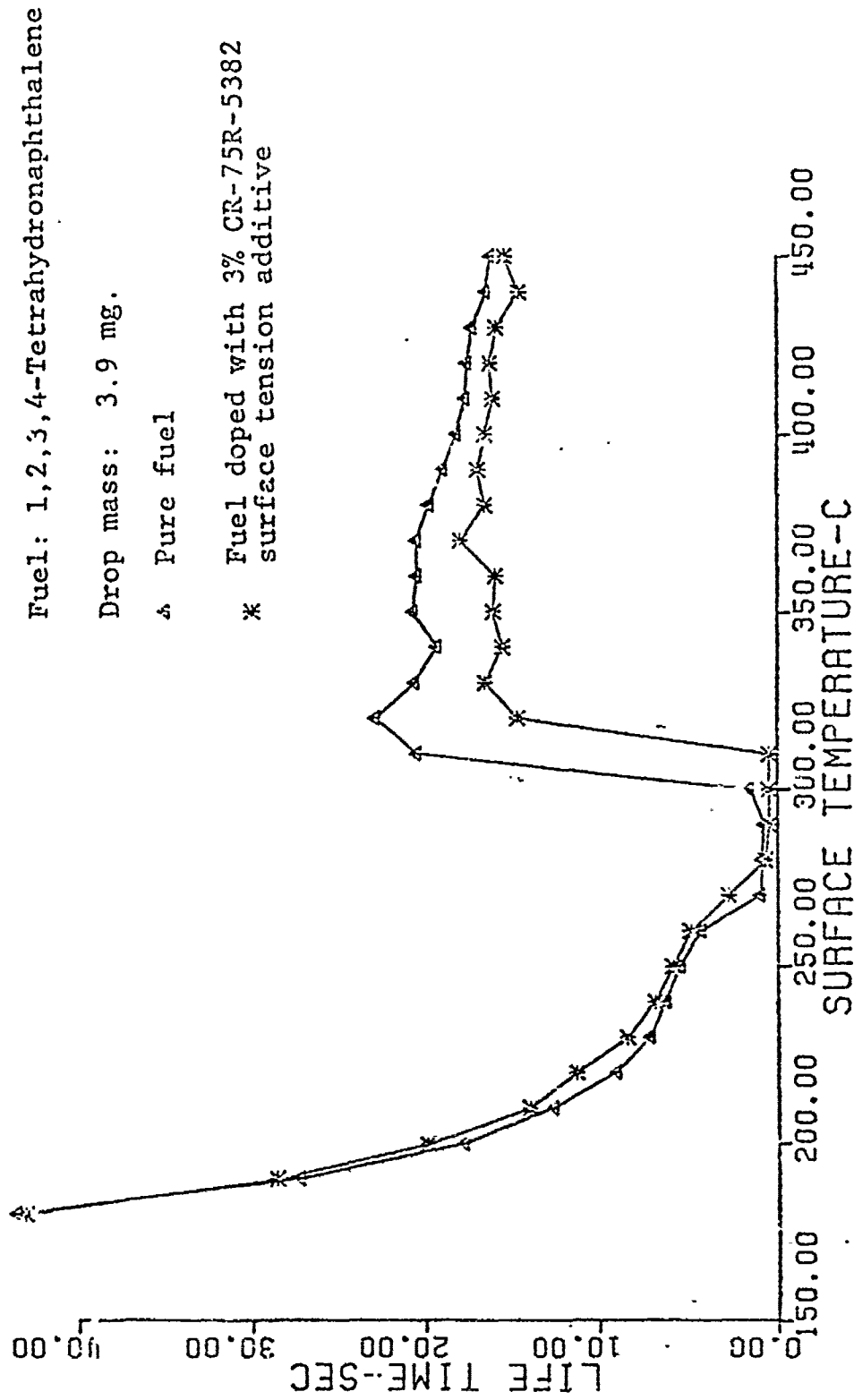Figure 23.  Effect of fuel surface tension on drop evaporation
lifetime.

Figure 24. Effect of fuel surface tension on drop evaporation lifetime.

the spheroidal mode and also due to the enclosure of vapor pockets within the drop as described earlier which caused micro explosion to occur and resulted in sudden and early termination of drop lifetime. Reducing the fuel surface tension also expanded the surface temperature range within which the maximum evaporation rate mode prevailed. Due to the restriction offered by the evaporating dish geometry, the spreading of the drops over the evaporating surface was not very effective and it was therefore felt that the reduction in drop evaporation lifetime in the contact mode was not as much as it would be if a flat evaporating surface was used. The figures clearly indicated that the effect of a specific fuel additive on the surface tension of the various types of fuels and on its evaporation behavior varied substantially with the type of fuel.

The effect of the additive blend ratio on the evaporation behavior of the drop was evaluated by blending CR-75R-5382 in 1 and 2 percent proportions with n-Hexadecane. The evaporation curves developed with the two fuel blends were then compared in Figure 25 with the evaporation behavior of a pure fuel. As can be seen from the figure, increasing the additive blend ratio further reduced the drop evaporation lifetime in all modes of evaporation. The expansion in the temperature range for the maximum evaporation rate mode also appeared to be dependent on the
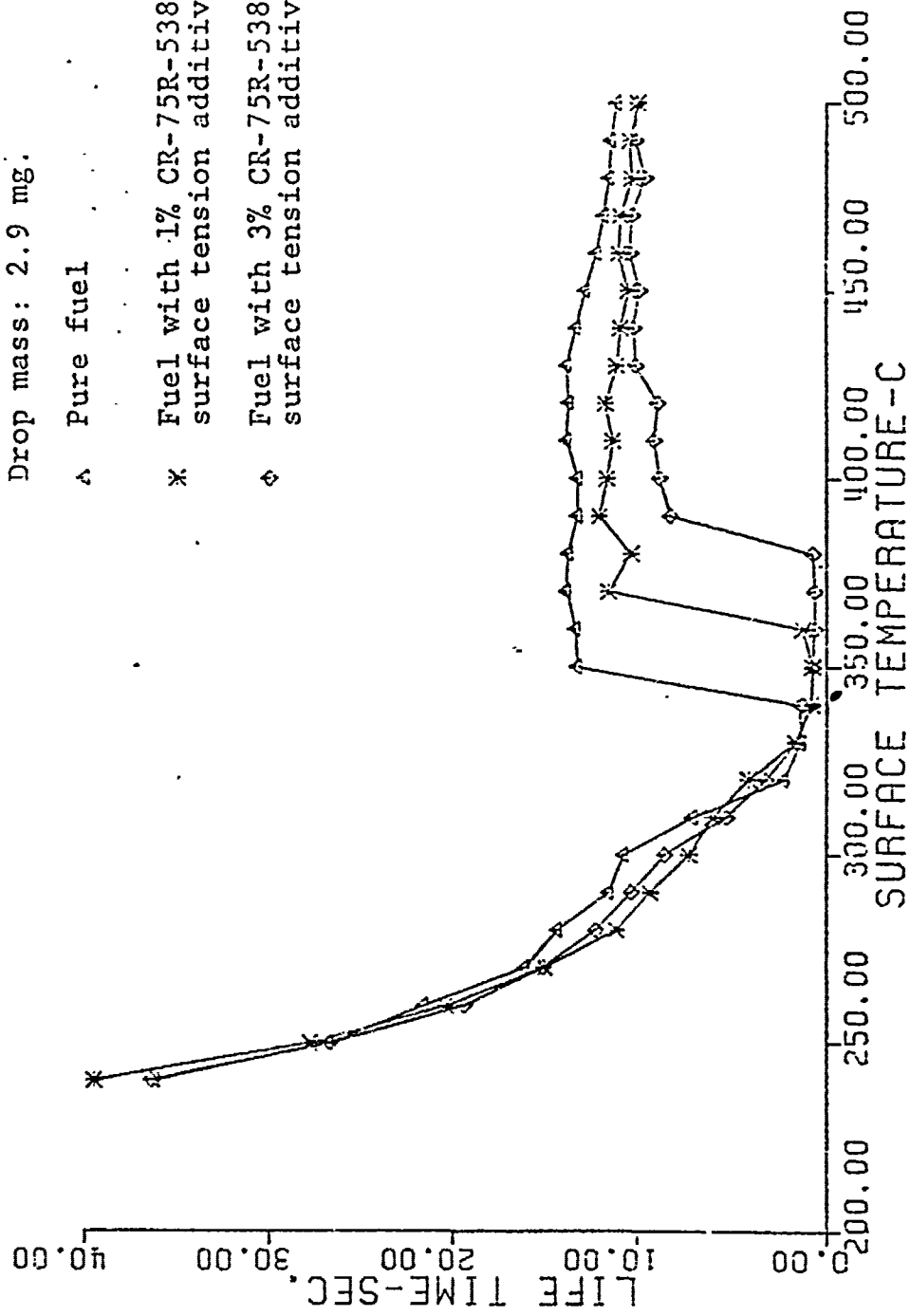
Figure 25. Effect of fuel surface tension on drop evaporation lifetime.

amount of additives used.

Four different types of surface tension additives
were blended with n-Hexadecane in the same proportion (3
percent) to identify the effect of different additives on
the evaporation behavior of the same type fuel. Evapora-
tion curves with the various fuel blends were developed and
compared in Figure 26 to the evaporation curve of the pure
fuel. The figure clearly showed that different additives
influenced the evaporation of a specific fuel by varying
degrees. The mechanism by which these additives brought
about the change in the surface tension characteristics of
the fuel is not, however, known. The reason that some
additives reduced the surface tension of a specific fuel
more effectively than others was not identified.

It is felt, based on the above results that surface
tension additives could be effectively used to expand the
temperature range of the maximum evaporation rate mode.
Great care should be exercised, however, in selecting the
additive that is most compatible to the fuel being used.

## Fuel Partial Vapor Pressure as a
### Function of its Temperature

Strong resemblance was noted between the shape of the
evaporation curve for the contact mode of evaporation and
the fuel partial vapor pressure curve as a function of its
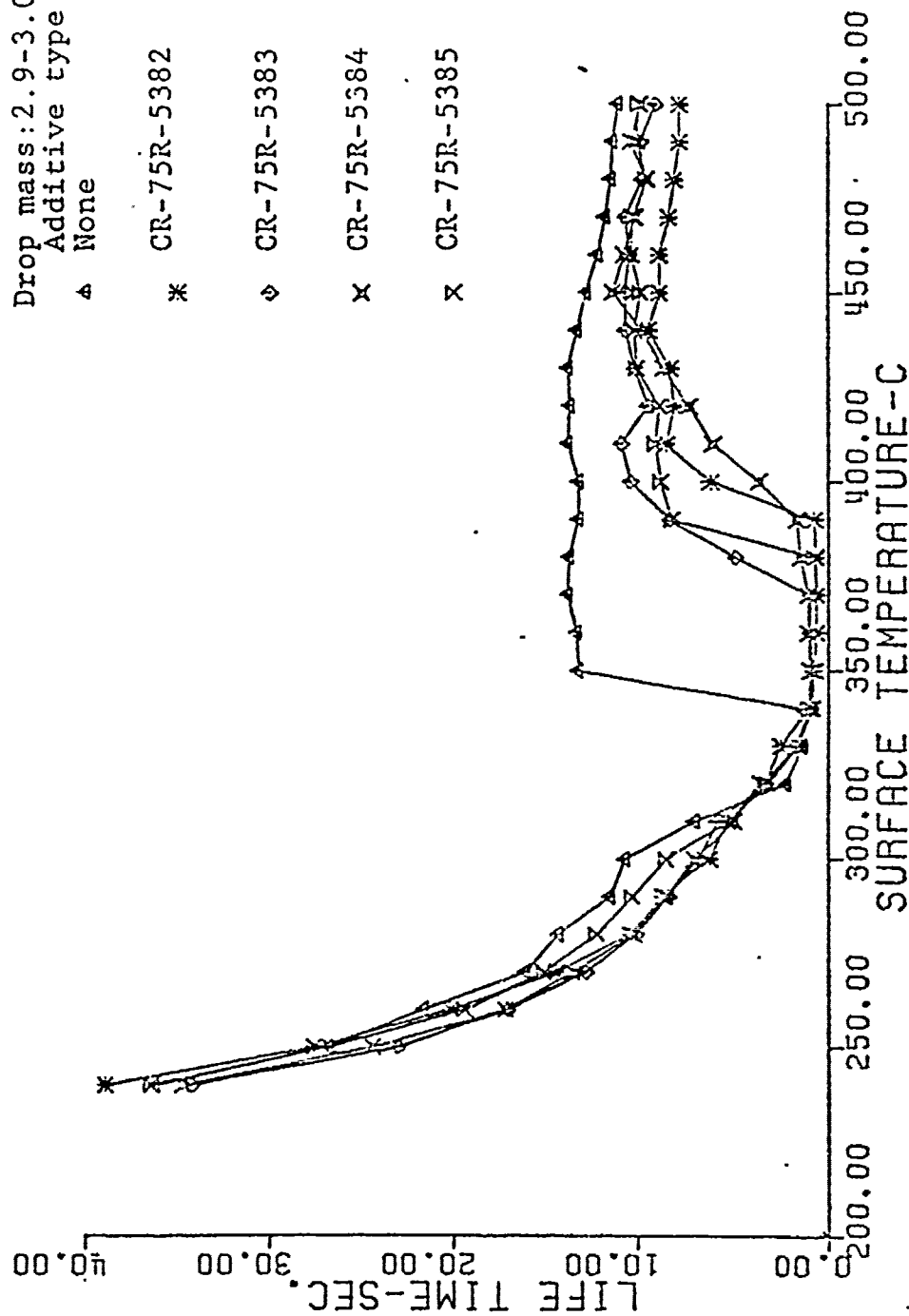
Figure 26. Effect of different types of surface tension additives on drop evaporation lifetime.

temperature. The similarity in the trends displayed by
the two curves implied that the driving force for drop
evaporation in this mode is the vapor pressure of the fuel.

To quantitatively examine the correlation between
the drop evaporation lifetime and the partial vapor
pressure of the fuel experimental data for the contact
mode using the results for two consecutive experimental
runs were fitted for a variety of fuels to the straight
line relationship.

$$\ln t = \frac{a}{T} + b$$

where

t     : Drop evaporation lifetime.

T     : Evaporating surface temperature.

a & b : Constants determined experimentally.

The relationship is essentially the Clausius-Clapeyron
equation for liquid vapor pressure after substituting for
the vapor pressure in the equation by the drop evaporation
lifetime, since they are as postulated above directly
proportional. The fitted curves for n-Heptane, 1-Octene,
1,2,3,4-Tetrahydronaphthalene, and n-Hexadecane were then
plotted in Figures 27 through 30 with the experimental data
to illustrate the close agreement between the two.

The figures clearly indicated that the agreement
between the fitted curve and the experimental results is

Figure 27.  The dependence of the drop evaporation lifetime in the contact mode of evaporation upon the vapor pressure of the fuel.

83
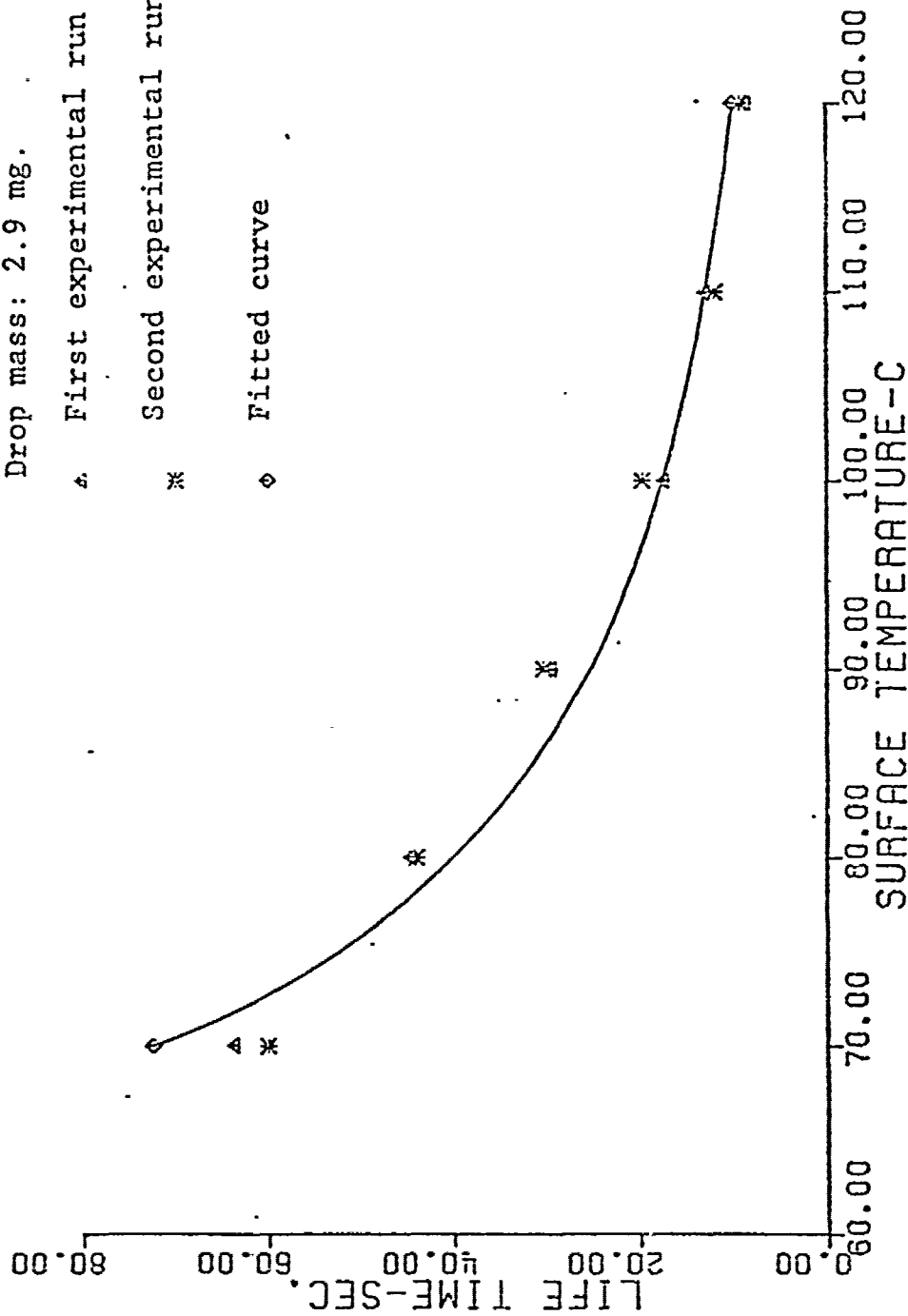


Figure 28. The dependence of the drop evaporation lifetime in the contact mode of evaporation upon the vapor pressure of the fuel.
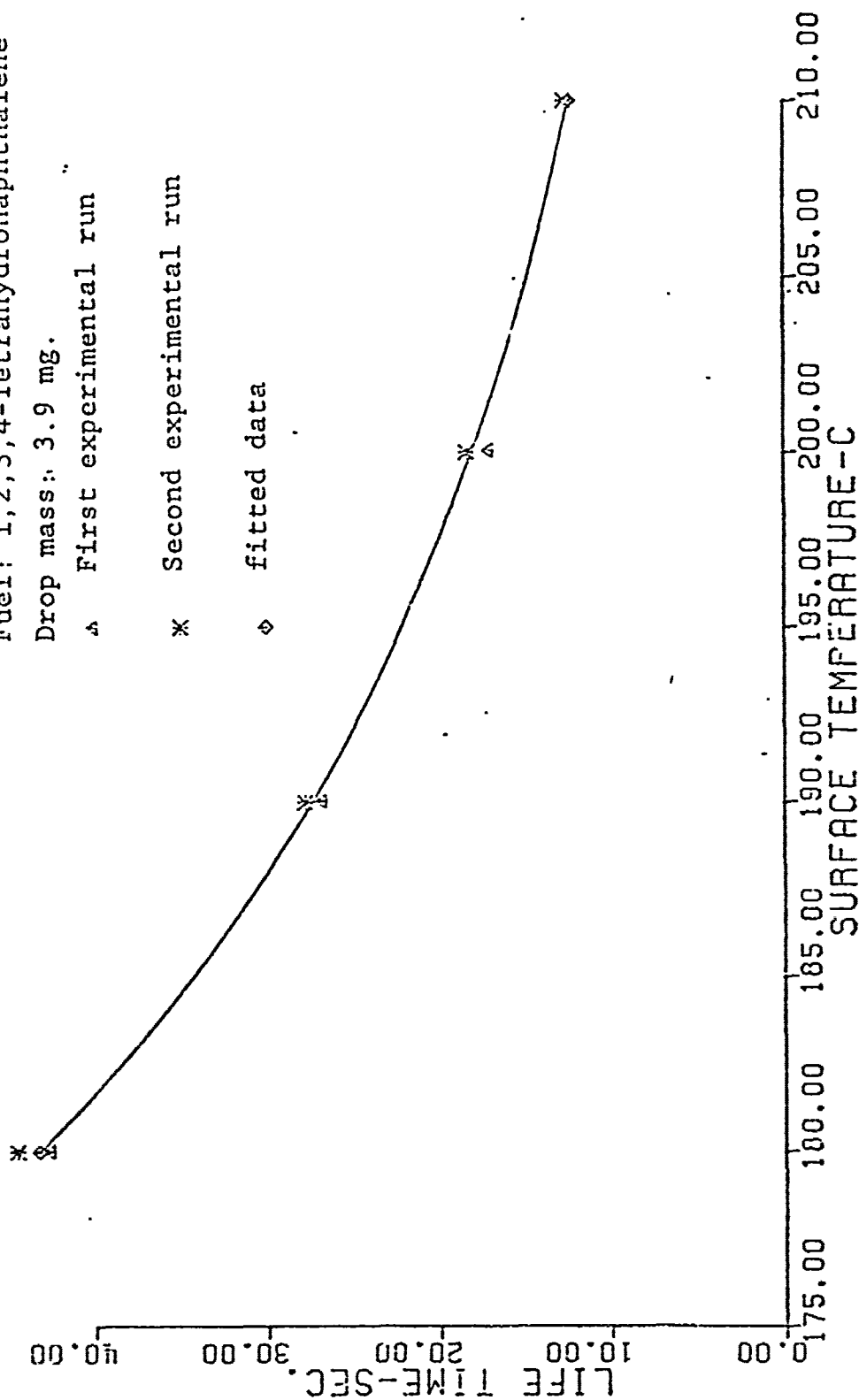
Figure 29. The dependence of the drop evaporation lifetime in the contact mode of evaporation upon the vapor pressure of the fuel.

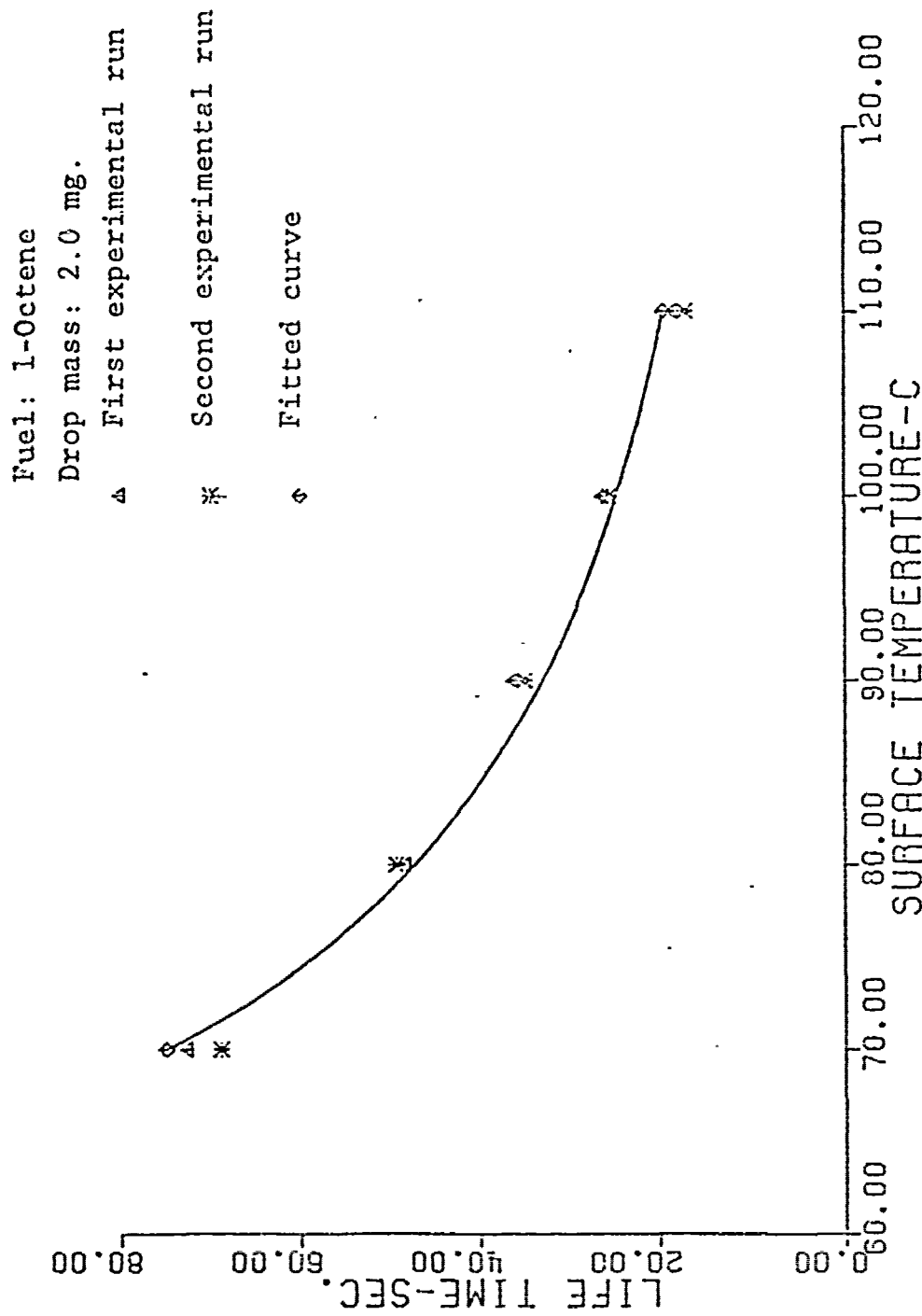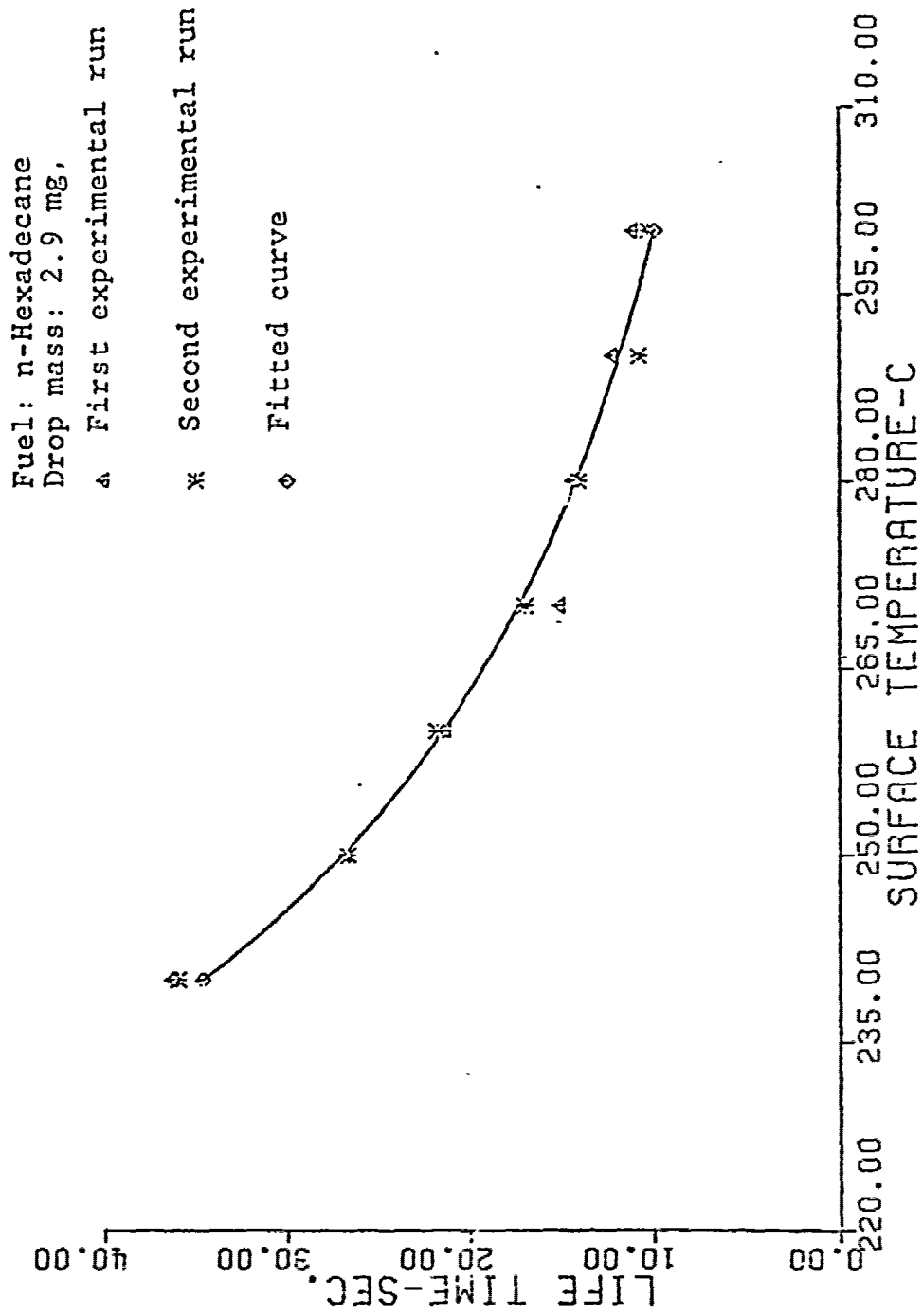Figure 30. The dependence of the drop evaporation lifetime in the contact mode of evaporation upon the vapor pressure of the fuel.

quite remarkable especially for 1,2,3,4-Tetrahydronaphtha-
lene and n-Hexadecane. The occasional deviation of the
experimental results off the fitted curve was attributed to
the experimental inaccuracy. In view of the fact that the
fuel drops used in conducting the experiments were
relatively very small in size, it is believed that thermal
equilibrium between the drop and the evaporating surface
was achieved in a very short period of time and drop
evaporation essentially commenced upon contact with the
surface. The scattering in the experimental results from
the fitted curve was also partly attributed to the
localized surface cooling introduced by the drop on the
surface causing the drop to reach an equilibrium tempera-
ture that is slightly lower than the surface temperature
reflected by the thermocouple reading.

It is concluded, based on the above results, that
the incremental reduction in drop evaporation lifetime due
to an increase in the surface temperature is proportionate
to the increase in fuel vapor pressure with temperature.
In comparing two different fuels, however, the drop
evaporation lifetime in the contact mode is predominantly
influenced, as discussed earlier, by the latent heat of
vaporization for the fuels.

## Latent Heat of Vaporization

The evaporation lifetime of fuel drops in the contact

and spheroidal modes of evaporation was found to be predominantly influenced by the latent heat of vaporization for the fuel. As was pointed out earlier, for drops of the same size, the evaporation lifetime for water for example was substantially higher than that of a pure hydrocarbon due to its high latent heat. In view of the complexity of the mechanism controlling the drop evaporation in these two modes, it was not possible, however, to establish a direct relation between the evaporation lifetime of the fuel drop and its latent heat of vaporization.

The evaporation of the fuel drops in the vaporization and in the maximum evaporation rate modes appeared on the other hand to be independent of the latent heat of vaporization of the fuel. By comparing the drop evaporation lifetime in the maximum evaporation rate mode for a variety of fuels and for different drop sizes in Table 3, it was noted that the evaporation lifetime for n-Hexadecane is consistently higher than that of other fuels. In view of the fact that n-Hexadecane has a low latent heat of vaporization and a surface tension that is comparable to other fuel, it is speculated that the driving mechanism that predominantly influenced the drop evaporation lifetime in this mode was the coefficient of boiling heat transfer.

In making such speculation, it is recognized that the amount of experimental data available is not sufficient

## TABLE 3

### COMPARISON OF THE DROP EVAPORATION LIFETIME IN THE MAXIMUM EVAPORATION RATE MODE FOR DIFFERENT TYPES OF FUELS

| Fuel Type | Drop Mass | $\Delta T^*$ | Drop life-time | Latent Heat of Vapori-zation | Surface Tension |
|---|---|---|---|---|---|
| n-Heptane | 1.9 | 51.6 | 0.65 | 76.1 | 20.26 |
| n-Heptane | 2.9 | | 0.95 | | |
| 1-Octene | 2.0 | 48.4 | 0.43 | 71.7 | 12.62 |
| 1,2,3,4-Tetra-hydronaphthalene | 3.9 | 63.2 | 0.95 | 79.3 | 34.34 |
| n-Hexadecane | 2.1 | 53.5 | 1.28 | 41.9 | 27.66 |
| n-Hexadecane | 2.9 | | 1.33 | | |
| n-Hexadecane | 3.8 | | 1.58 | | |
| n-Hexadecane | 4.3 | | 1.63 | | |
| Water | 2.1 | 70.0 | 2.65 | 100.0 | 72.75 |

*Temperature increment above the fuel boiling temperature for the maximum evaporation mode to occur.

to justify a reliable conclusion. Therefore, it appears that further research must be conducted using a wider variety of fuels and more elaborate drop lifetime measuring techniques in order to better understand the evaporation behavior of the fuel drops in this mode. In case the drop lifetime was truly controlled by the boiling coefficient for heat transfer of the various fuels, it seems promising that this technique be used to obtain a quantitative measure for the boiling heat transfer coefficients for the different types of fuels.

## Fuel Specific Heat

The effect of the specific heat of the fuel on drop evaporation was noted in the contact mode of evaporation. It was found that localized surface cooling is introduced in this mode by the drop during its initial contact with the surface in order to achieve thermal equilibrium with the surface. As indicated earlier the time required for the drop to reach thermal equilibrium was judged, based on experimental observation, to be insignificant compared to the evaporation lifetime of the drop. The degree of localized surface cooling introduced on the surface was obviously dependent upon the mass of the drop and the fuel specific heat.

To examine the effect of localized surface cooling

on drop evaporation, the drop evaporation lifetime for
n-Heptane in the contact mode using the surface with
evaporating dishes was plotted in Figure 31 against its
mass. As can be seen from the figure, at a constant sur-
face temperature the evaporation lifetime of the fuel drops
increased linearly with the drop mass. It was noted,
however, that the rate of increase in drop lifetime (slope
of the straight lines) decreased steadily with the increase
in the surface temperature. The results indicated that the
degree of localized surface cooling is influenced by the
surface temperature and/or its geometry.

To eliminate the effect of the surface geometry,
evaporation curves were developed for the contact mode
using several fuel drop sizes on flat stainless steel and
aluminum surfaces. The drop evaporation lifetime obtained
on both surfaces were again plotted against the drop mass
in Figure 32. The figure showed that for a specific
evaporating surface the increase in drop lifetime with its
mass is constant for the different surface temperature.
This clearly indicated that the variation in the slope of
the straight line that was initially experienced was
mainly caused by the geometry of the evaporating surface.
Allowing the drop to spread freely over the flat surface
caused the thickness of the liquid layer above the surface
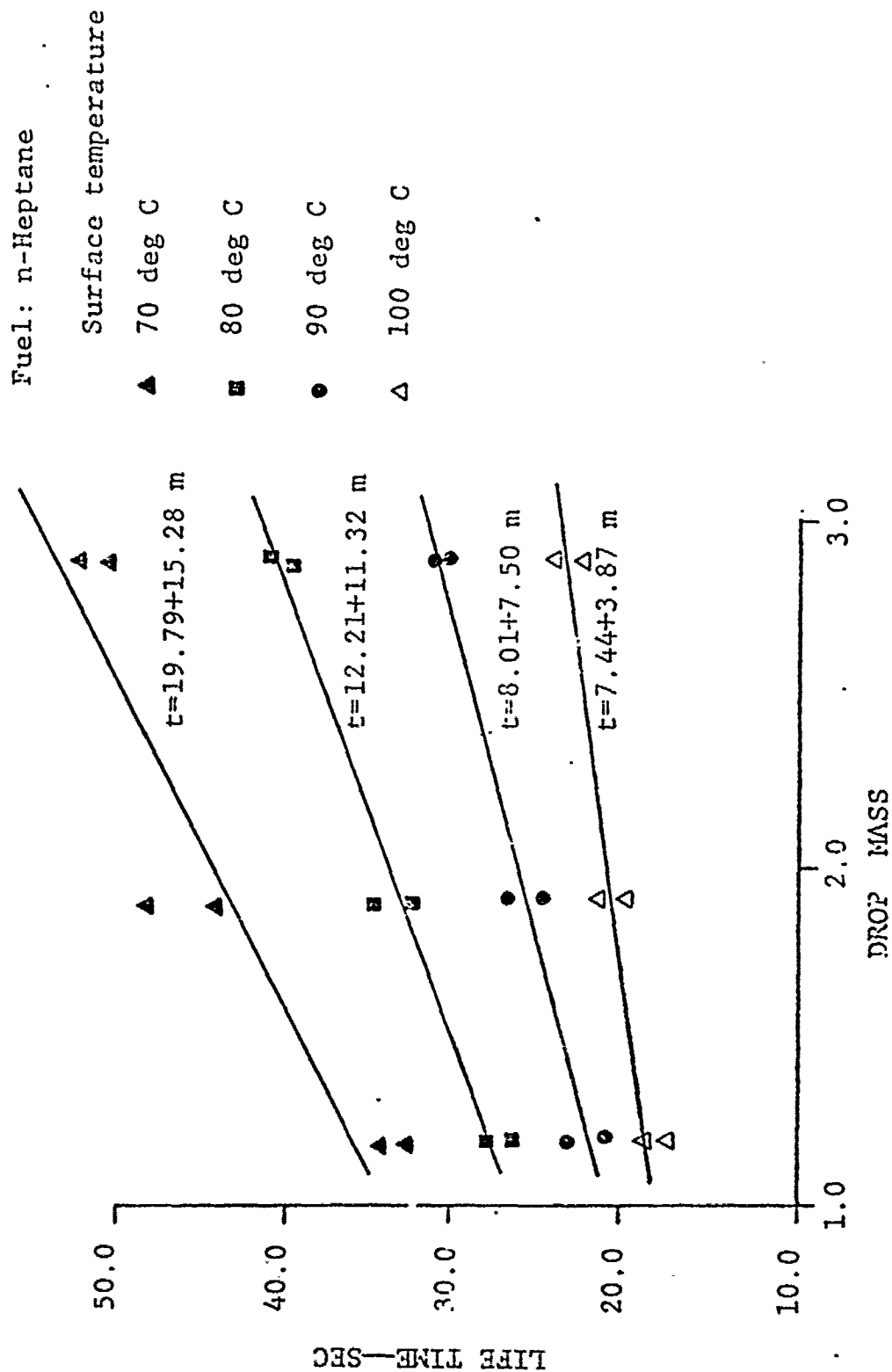to be uniformly constant, and the area of contact between

Figure 31. Effect of localized surface cooling on drop lifetime in the contact mode of evaporation.
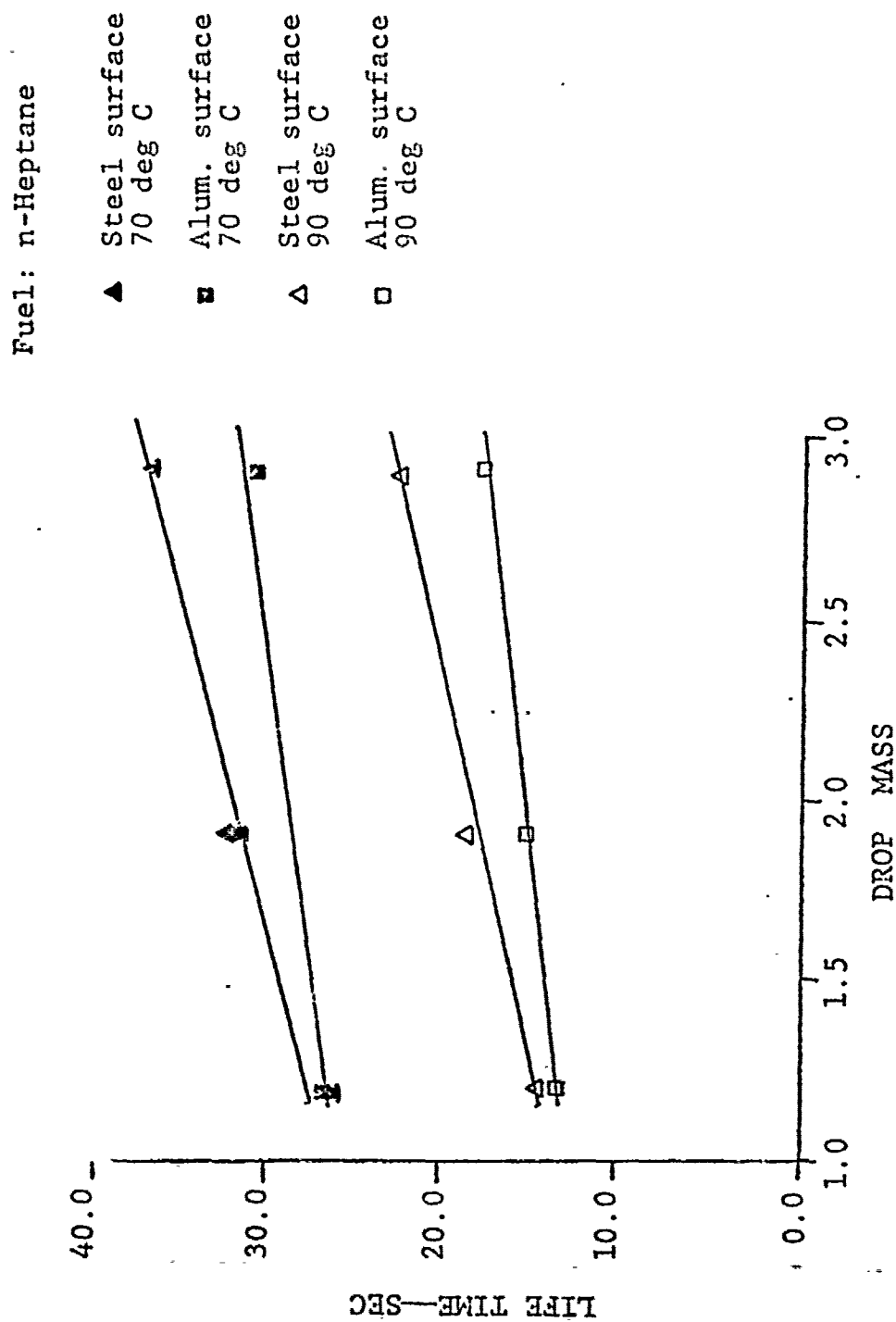
Figure 32. Effect of evaporating surface geometry and thermal conductivity, on evaporation in the contact mode.

the drop and the surface to be proportionate to the drop size. The conduction of heat within the evaporating surface to the area of contact between the drop and the surface was also more effective when the flat evaporating surface was used.

The increase in the drop evaporation lifetime with its mass was also found as shown in Figure 32 to be dependent upon the thermal conductivity of the evaporating surface. For surfaces of a high thermal conductivity, such as aluminum, the increase in drop lifetime as a function of its mass was relatively smaller than that for a stainless steel surface. T'⸱ results strongly implied that the increase in drop ⸱time as a function of its mass at a constant surface temperature is merely due to the localized surface cooling that is introduced by the larger fuel drops on the surface. The degree of the localized surface cooling was obviously dependent upon the drop mass and therefore larger fuel drops were generally exposed to lower local surface temperature. The lower the surface temperature or the more intense the localized surface cooling, the longer the drop evaporation lifetime. It is also apparent, based on the above results, that the increase in the drop lifetime as a function of its mass is very dependent upon the specific heat of the fuel.

It is postulated in light of the above results that

the evaporation lifetime of fuel drop in the contact mode
at a constant surface temperature will be essentially
independent of its mass if a smooth flat evaporating sur-
face of an infinitely high thermal conductivity was used in
conducting the experiment. To substantiate such postulate
it is recognized that additional experimental investigation
should be conducted. The experimental results obtained
until now, however, strongly support previously presented
postulate indicating that the drop evaporation lifetime in
the contact mode is mainly influenced by the increase in
the fuel vapor pressure as a function of its temperature.

## Effect of Commercial Fuel Additives on
### the Combustion Qualities of Fuels

The evaporation of a single fuel drop on a hot
surface was used to qualitatively examine the mechanisms by
which fuel additives that are available commercially
influenced the combustion of fuels. The additives tested
included Isomyl nitrate and Aniline which are generally
used as cetane rating improver in diesel engine application;
Appollo gas turbine Smoke Suppressor used by utility
companies to reduce smoke emission from gas turbines and
Ethyl - Diesel ignition improver 2, manufactured by the
Ethyl Corporation to enhance fuel combustion in a diesel
engine.

To evaluate the effect of the considered additives on the evaporation and combustion qualities of a single fuel drop, the Isomyl nitrate and Aniline additives were blended in 1 percent volumetric proportions with n-Hexadecane. The evaporation curves developed for the doped and pure fuels were then compared for the contact mode of evaporation in Figure 33. The Appollo smoke suppressor was also blended in 3 percent volumetric proportion with n-Heptane and evaporation curves for the doped and pure fuels were compared in Figure 34. It appeared from the figures that the effect of the tested additives on the fuels evaporation is quite similar to that of additives used to reduce the surface tension of the fuel. It was not known, however, if the reduction of the surface tension of the fuel is the cause for the improvement in its combustion quality.

Based on the results presented in this study, it has been shown that reducing the fuel surface tension expands the temperature range within which the maximum evaporation rate mode occurs for fuel deposited on a hot surface. It is also known that reducing the fuel surface tension improves the atomization characteristics of the fuel and enhances its rapid vaporization. It is therefore speculated that reducing the fuel surface tension may in general improve its combustion quality. Extensive research
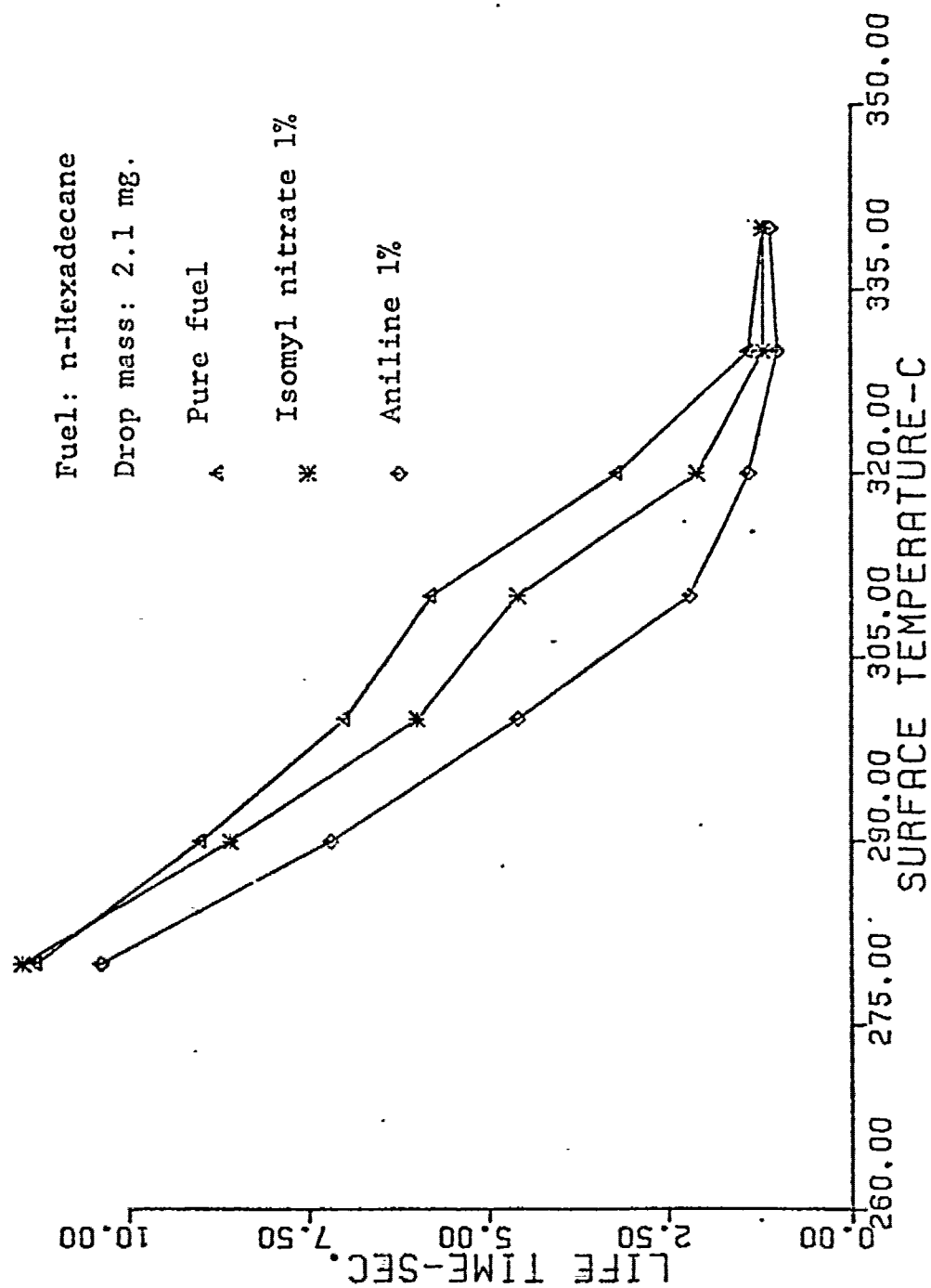
Figure 33.   Effect of diesel cetane improver on the evaporation behavior of a fuel drop.
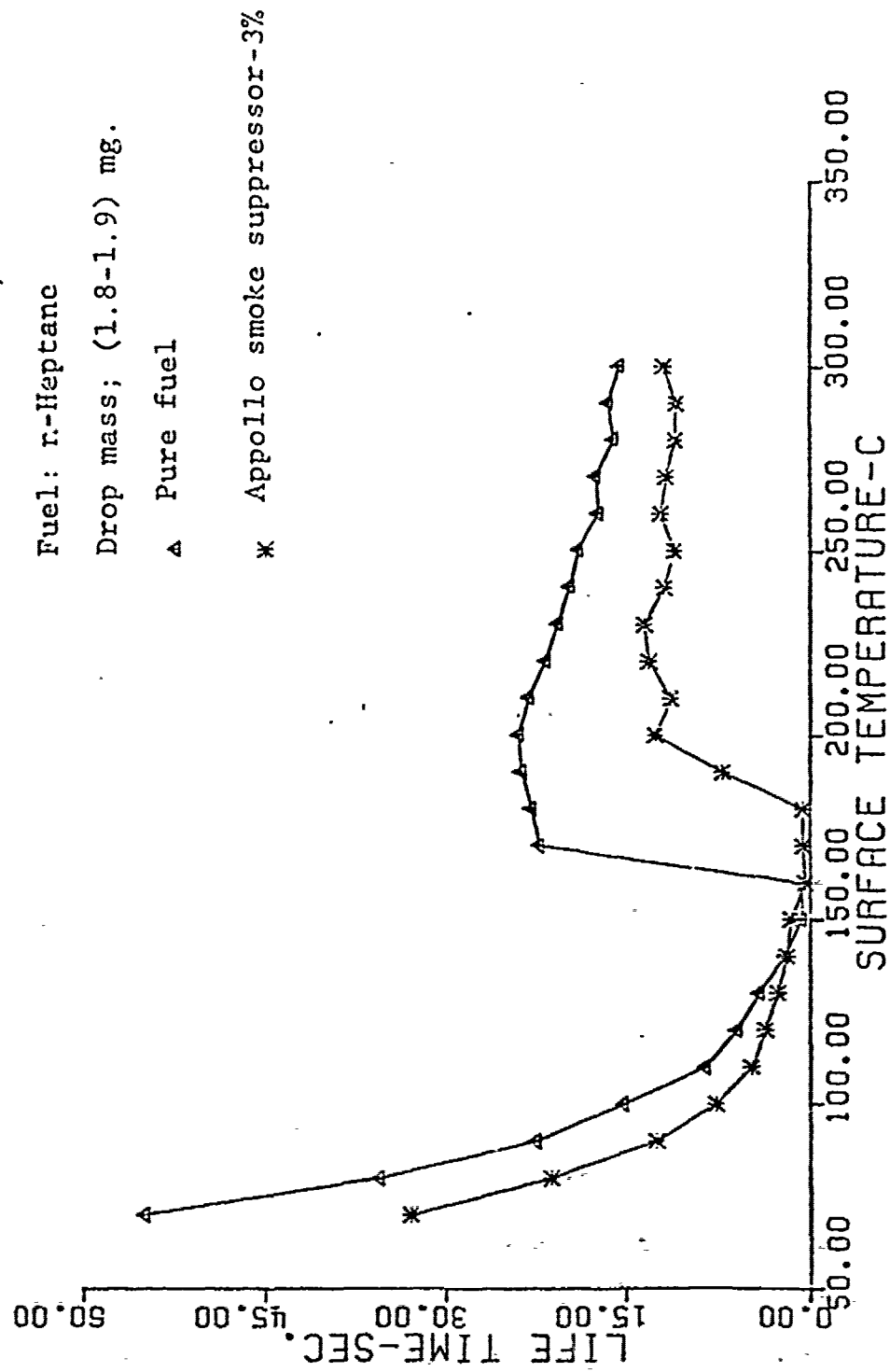
Figure 34.    Effect of the Appollo smoke suppressor on the
evaporation behavior of fuel drops.

in practical combustion apparatus is required, however, to substantiate such speculation.

Evaporation curves were also developed when the ethyl-ignition improver 2, was blended in 3 percent volumetric proportion with n-Hexadecane. The developed evaporation curves for the pure and doped fuels were compared in Figure 35. The figure showed that the ignition improver, in general, did not significantly influence the evaporation behavior of the fuel. The additive, as expected, however, caused ignition to occur during all modes of drop evaporation starting at a surface temperature of 290 degrees C. It was surprising to note that the lifetime of the fuel drop was not affected by its combustion. The results of the test also showed that the used additives achieved the combustion of the fuel vapor at temperatures significantly below its self-ignition temperature and at stoichiometric proportions that may be outside the flammability limits.

## Effect of Experimental Procedures
## on the Test Results

The effect of the experimental procedures on the test results were examined in an effort to explain the cause for the discrepancies noted between the results reported by previous investigators. The experimental

Fuel: n-Hexadecane

Drop mass:(2.9-3.0) mg.

▲ Pure fuel

✳ 3% diesel ignition improver

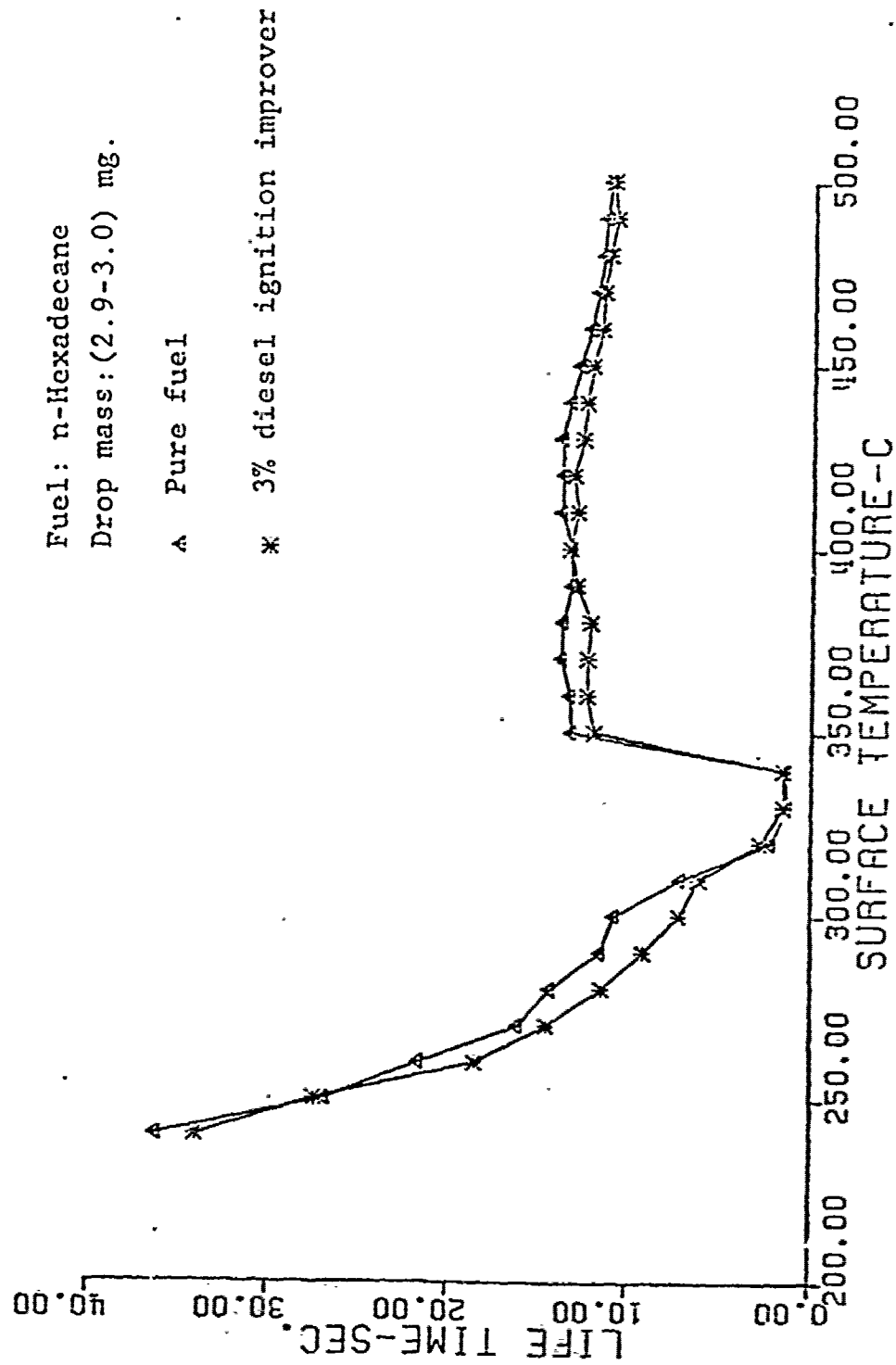LIFE TIME-SEC.

SURFACE TEMPERATURE-C

Figure 35.  Effect of ethyl-ignition improver 2 on the evaporation
behavior of fuel drops.

procedures that were considered during the evaluation
included the surface cleanliness, fuel drop size and
evaporating surface heating rate. The effect of the
studied variables on the test results was found to be as
follow:

## Surface Cleanliness

As indicated earlier, previous investigators have
developed their evaporation curves by depositing the fuel
drops in a single spherical depression machined on the
evaporating surface. It was pointed out that the fuel
residue left on the surface influenced the drop evaporation
lifetime and limited the ability to reproduce the test
results.

To illustrate the effect of surface cleanliness on
drop evaporation, curves were developed using a single
dish for the evaporation of all fuel drops as was performed
by previous investigators. The developed evaporation
curves were then compared in Figure 36 to the evaporation
curve for the same type fuel and the same size fuel drops
developed using multi-evaporating dishes for the evapo-
ration of the drops. The figure showed that a reduction
in drop lifetime occurs in the contact mode of evaporation
as a result of evaporating the fuel drops in the same
location. It was also noted that the temperature range

Fuel: n-Hexadecane
Drop mass: 2.9 mg.

▲ Multi-evaporating dishes

✳ Same evaporating dish

◇ Same evaporating dish

✕ Same evaporating dish

⊡ Same evaporating dish, fast fuel feeding rate
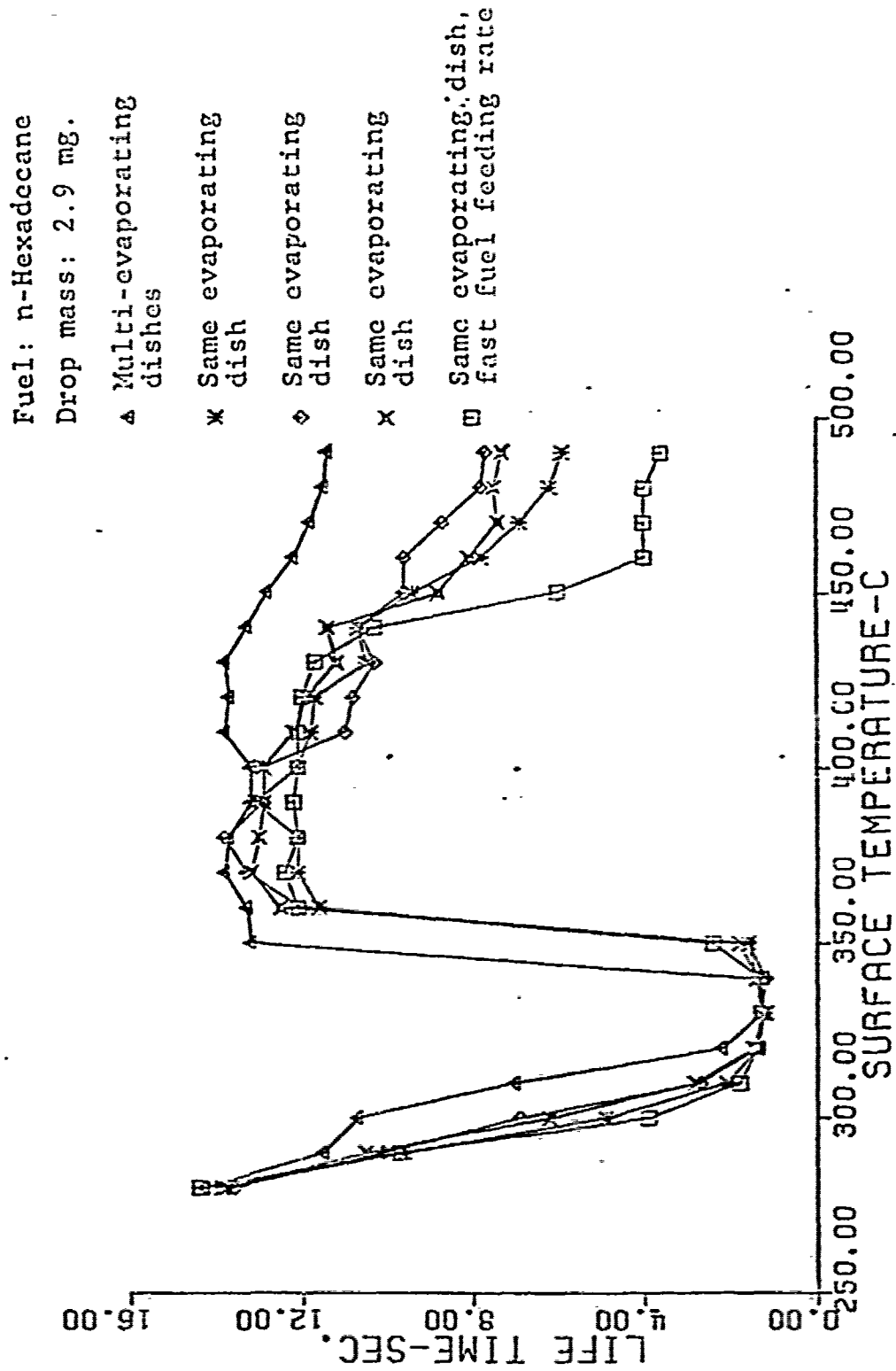
**SURFACE TEMPERATURE—C**

**LIFE TIME—SEC.**

Figure 36.   Effect of surface cleanliness on drop evaporation lifetime.

within the maximum evaporation rate mode occurs was

expanded by making the surface dirty. The lifting into

the spheroidal mode was delayed and significant reduction

in drop lifetime was experienced in the spheroidal mode due

to the carbon and gummy deposits that formed on the surface.

There were four different evaporation curves as

shown in Figure 36 developed by depositing the fuel drop

in the same location on the surface. In the first three

curves, the fuel drops were fed onto the evaporating

surface at a moderate rate. In the fourth evaporation

curve , to further aggravate the deterioration in the

surface quality, fuel drops were deposited in the same

location onto the evaporating surface at a relatively fast

rate. It was noted that the reduction in drop lifetime in

all modes of evaporation and especially in the spheroidal

mode increased with the increase in fuel feeding rate on

the evaporating surface. This  clearly indicated that the

deterioration in surface quality is the main cause for

the noted reduction in drop lifetime.

It is quite evident in light of the above results

that the evaporation lifetime reported by previous inves-

tigators was influenced by the quality of the evaporating

surface. The degree by which surface quality affected

drop lifetime in the various investigations varied, however,

as a function of the frequency by which the fuel drops were

deposited onto the surface. The deterioration in the
surface quality was also affected by the experimental
procedure, adopted by the various investigators, in which
the method of cleaning the evaporating surface and the
frequency of which the surface was to be cleaned were
established.

## Fuel Drop Size

The effect of the fuel drop size on its evaporation
lifetime was only identified during this study for the
contact and spheroidal modes of evaporation. In the
contact mode, the amount of localized cooling introduced by
the drop on the evaporating surface was dependent, as
discussed earlier, upon the size of the fuel drops used.
Larger drops, as to be expected, caused a more significant
reduction in the evaporating surface temperature to occur
locally at the area of contact between the drop and the
surface. The lower local temperature to which the larger
fuel drops were exposed to, increased its evaporation
lifetime. In the spheroidal mode of evaporation, smaller
fuel drops were found as shown in Figure 37 to achieve
lifting at a lower surface temperature. The smaller drops
by virtue of    light weight required a very small
fraction of the fuel to evaporate to cause lifting to occur.
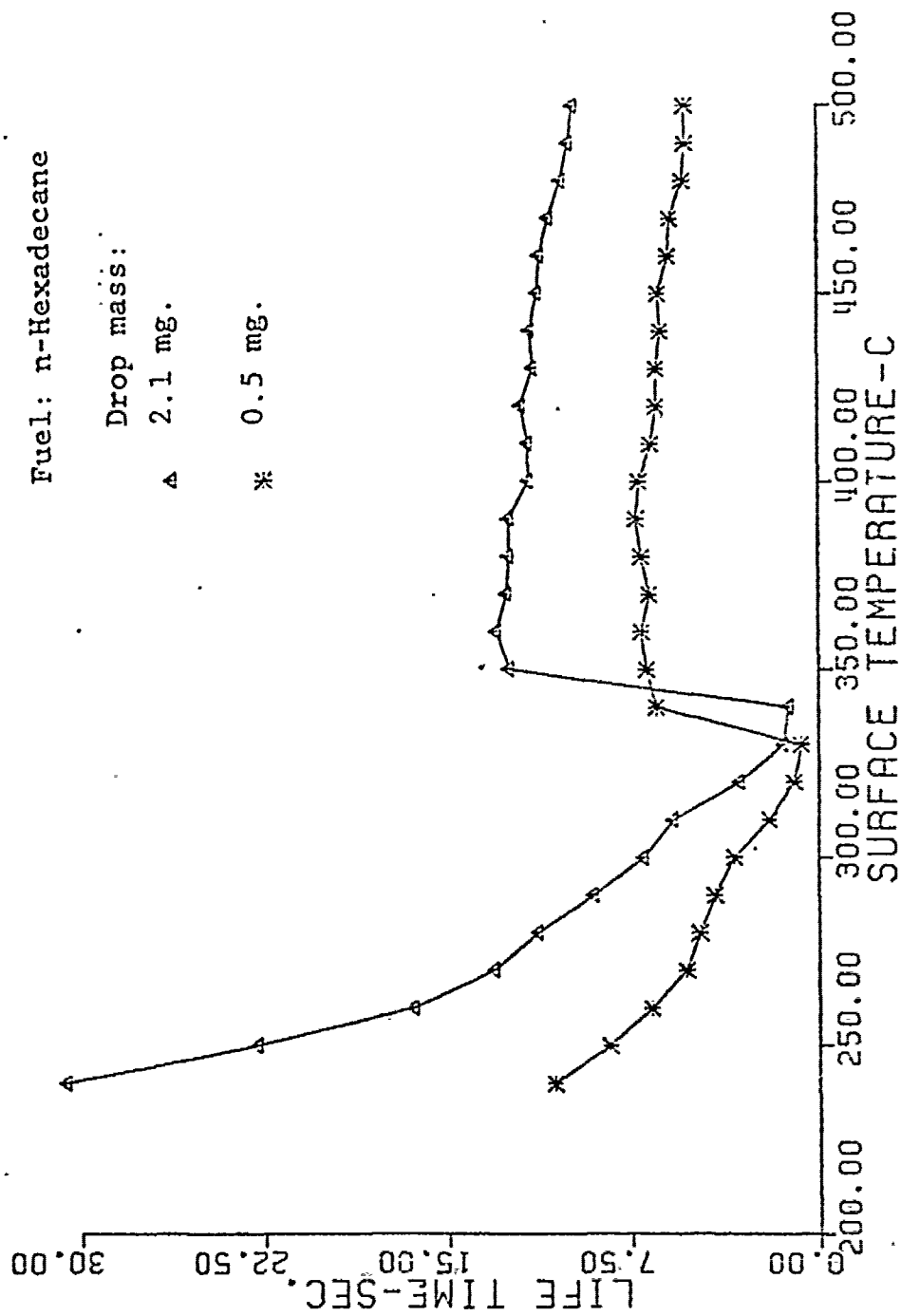The intensity of the localized surface cooling introduced

Figure 37.    Effect of drop size on the surface temperature for
spheroidal lifting.

by the small drops was as a result less significant, and
therefore  the lifting of the drop materialized at a lower
surface temperature.

The size of the fuel drop appeared important in the
spheroidal mode of evaporation since it controlled the
thickness of the vapor cushion underneath the drop across
which heat is transferred from the surface. to the drop.   To
examine the effect of the drop size on its evaporation
lifetime in this mode, a plot was constructed in Figure 38
between the drop evaporation lifetime and the reciprocal
of the temperature potential driving the heat transfer from
the surface to the drop.   The temperature potential was
calculated by substracting the fuel boiling temperature
from the temperature of the evaporating surface.   The
figure showed that for a specific drop size a linear
relation exists between the drop lifetime and the reciprocal
of the temperature difference between the drop and the
surface.   The result supported previously presented
postulates indicating that the controlling mechanism for
the drop lifetime in the spheroidal mode is heat transfer.
It was also noted, from the figure, that the slope of the
straight line relationship between the drop lifetime and
the reciprocal of the temperature potential varied with the
change in the drop mass.   A more steep slope was displayed
by the lines for the larger fuel drops indicating that
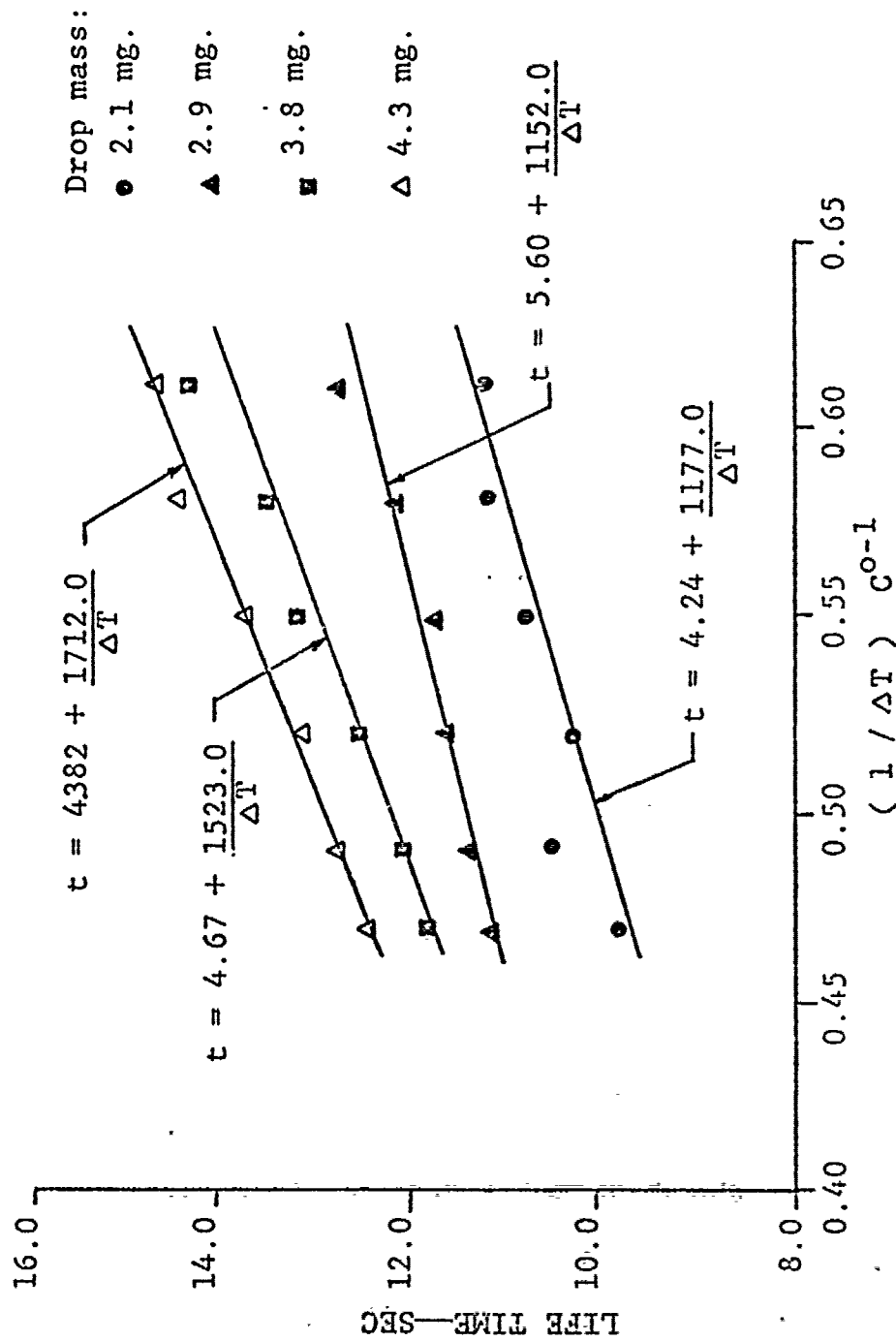the drop evaporates while it is setting closer to the

Figure 38. Effect of the drop mass on the vapor cushion thickness forming underneath the drop in the spheroidal mode of evaporation.

surface with a relatively thinner vapor cushion layer. The drop evaporation lifetime in the spheroidal mode was not, as a result, exactly directly proportional to the drop mass due to the variation in the vapor cushion thickness underneath the drop.

## Evaporating Surface Heating Rate

The effect of the evaporating surface heating on drop lifetime was more pronounced as shown in Figure 39 in the contact mode of evaporation due to the sensitivity of drop lifetime in this mode to variation in the surface temperature. The high heating rate has in general, however, resulted in a reduction in drop lifetime in all modes of evaporation. The surface temperature at which the various modes of evaporation commenced was essentially unaffected by the variation in the evaporating surface heating rate.
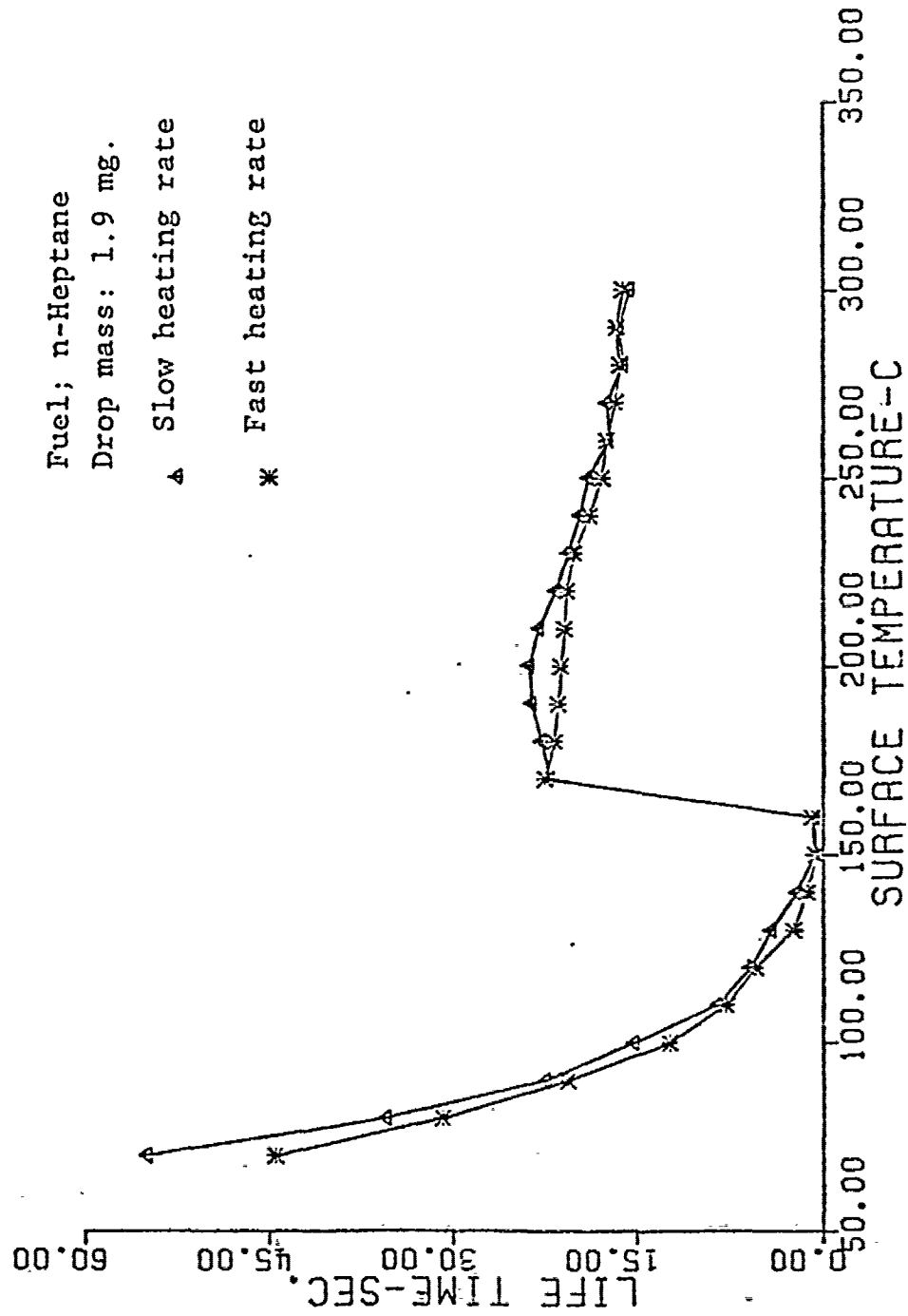
Figure 39    Effect of evaporating surface heating rate on drop
             evaporation lifetime.

## CONCLUSIONS

Based on the results presented in this final report, the following conclusions were made:

(1) Fuel drops deposited on a hot surface evaporate in four basic modes of evaporation; the contact mode, vaporization mode, maximum evaporation rate mode, and the spheroidal mode. The surface temperature at which transition from one mode of evaporation to another occurs is strongly dependent upon the fuel boiling temperature, surface tension, latent heat of vaporization, and specific heat, and upon the characteristics of the surface..

(2) The surface temperature range within which the maximum evaporation rate mode occurs could be expanded appreciably by:

   i- Reducing the fuel surface tension.

  ii- Reducing the interfacial surface tension between the fuel and the surface.

 iii- Increasing surface roughness.

iv- Use surfaces covered with carbon and
gummy deposits.

(3) The surface temperature at which transion occurs
from one mode of evaporation to another is
directly proportional for pure fuels evaporated
on a polished metal surface to the boiling
temperature of the fuel. Fuels of high latent
heat of vaporization, specific heat and/or low
surface tension may deviate, however, from this
dependence.

(4) For pure fuels evaporated on a polished metal
surface the surface temperature at which the
spheroidal mode of evaporation commences is
dependent upon the fuel boiling temperature,
surface tension, latent heat of evaporation and,
to a lesser degree, its specific heat.

(5) For pure fuels evaporated on a polished metal
surface the surface temperature at which the
vaporization and maximum evaporation rate mode
occur is mainly dependent upon the fuel surface
tension an. boiling temperature.

(6) The reduction in drop evaporation lifetime in
the contact mode due to an increase in the
surface temperature is proportianal to the
increase in fuel's vapor pressure with tempera-

ture. The controlling mechanism for the drop evaporation rate in this mode is the diffusion of fuel vapor at the drop phase boundary that is exposed to the atmosphere.

(7) The drop evaporation lifetime in the contact and spheroidal modes is predominantly influenced by the latent heat of vaporization for the fuel. In the vaporization and maximum evaporation rate modes, the drop lifetime is postulated to be influenced by the fuel boiling coefficient of heat transfer.

(8) The drop evaporation lifetime in the contact mode is influenced by the drop mass, fuel specific heat, and evaporating surface thermal conductivity.

(9) A linear relationship exists between the drop evaporation lifetime in the spheroidal mode and the reciprocal of the temperature difference between the surface and the fuel. The slope of the straight line relationship is directly proportional to the mass of the drop.

(10) The decrease in the evaporation lifetime of the fuel drops in the spheroidal mode with respect to the increase in the surface temperature is inversely proportional to the boiling tempera-

ture  of the fuel.

(11) Reducing the surface tension of the fuel reduces
the drop evaporation lifetime in all modes of
evaporation.

(12) It appears based on the qualitative evaluation
conducted of commercial fuel additives that
reducing the surface tension of the fuel may
improve its combustion qualities.

(13) The evaporation lifetime of a fuel drop is
significantly reduced in all modes of evaporation
when a rough surface or surface covered with
carbon deposits is used for the evaporation of
the drops.

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The evaporation of a fuel drop on a hot surface was investigated for a variety of pure and commercial fuels under atmospheric ambient pressure. Four basic modes of drop evaporation were identified; the contact mode, vaporization mode, maximum evaporation rate mode, and spheroidal mode. High level of experimental reproducibility was achieved for the pure fuels and the experimental variables that influenced the reproducibility of the test results were successfully identified. The effect of fuel properties on drop evaporation lifetime in the various modes of evaporation was closely examined. Fuel properties that

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or controlled the temperature range within which the various modes of evaporation prevailed were determined. Evaporation curves were developed for the tested fuels using a wide selection of surface conditions, some of which resembled surface characteristics encountered in actual combustion applications. The effect of the evaporating surface characteristics on evaporation lifetime was also determined. The effect of fuel additives on the evaporation behavior of fuel drop deposited on a hot surface was evaluated. The mechanisms by which a variety of commercial fuel additives brought about an improvement in the combustion qualities of fuels were broadly discussed. Techniques to broaden the temperature range within which the maximum rate of drop evaporation is obtained were recommended.